IN: Gann, R.G., Editor, Fire Suppression System Performance of Alternative Agents in Aircraft Engine and Dry Bay Laboratory Simulations, Vol. 1, Section 2, NIST SP 890, 9-75 pp, 1995

2. SUPPRESSION OF HIGH SPEED FLAMES AND QUASI-DETONATIONS

Grzegorz W. Gmurczyk
Science Applications International Corporation
and
William L. Grosshandler
Building and Fire Research Laboratory

Contents

2.1 Background

A dry bay is a normally confined space adjacent to a fuel tank in which a combustible mixture and an ignition source could co-exist following penetration by an anti-aircraft projectile. They vary considerably in volume, typically being in the range of 0.2 to 3.0 m^3. They are located in the wings and fuselage, and their shape is most often irregular. Aspect ratios up to 10:1 are not uncommon. The bays may or may not be ventilated, and are usually cluttered with electronic, hydraulic and mechanical components. Compared to the events leading to engine nacelle fire suppression, the required timing is two orders-of-magnitude faster for dry bay protection.

The previous study using a deflagration/detonation tube (Grosshandler *et al.*, 1994) was concerned with establishing a comprehensive experimental program to screen the performance of over a dozen agents. The experiments were designed to cover the range of conditions that might occur in a dry bay. Although actual measurements of fuel concentrations in a dry bay during live-fire testing have never been made, one could envision a worst-case situation in which the fuel is vaporized and partially premixed with the air just prior to ignition, producing a rapidly moving turbulent flame. If the suppressing agent were not well mixed and the dry bay geometry were conducive, the turbulent flame could accelerate, generating a shock wave ahead of it and transitioning to a detonation before encountering the agent. Ethene was chosen as the fuel in the previous study because it was known to detonate easier than many other hydrocarbons. This provided the most severe test for all the agents under conditions that were not duplicated in any of the other bench-scale studies.

Three chemicals were selected by the Technology Transition Team to be included in the complete full-scale experimental matrix conducted at Wright Patterson AFB (Carbaugh, 1993): HFC-125, FC-218 and CF_3I. Measurements in the previous detonation/deflagration tube study revealed a volume factor (VF) for FC-218 that was lower than the VF for HFC-125. More significant was the high over-pressure experienced for HFC-125 mass fractions below 25 %. With the deflagration/detonation tube operating with a lean ethene/air mixture, 21 % HFC-125 in the test section produced a quasi-detonation with a pressure ratio of 37:1, double the pressure build-up when no agent was present. The FC-218 behaved quite differently, and effectively reduced the pressure ratio at concentrations near 21 %. These results favored the selection of FC-218 over HFC-125 for dry bay protection.

Few flame suppression experiments had been conducted with CF_3I that were applicable to dry bays. The previous detonation/deflagration tube results indicated an unusual behavior that could also be observed with CF_3Br, but to a lesser extent. Both chemicals were equally effective in low concentrations at reducing the pressure build-up. At mass fractions greater than about 10 % the chemistry is altered and the pressures began to rise. Increasing the CF_3Br concentration benefitted suppression at mass fractions greater than 20 %, and total suppression of the flame occurred above 30 %. Pressure ratios in the CF_3I tests continued to rise up to a mass fraction of 30 %, reaching a pressure greater than the uninhibited mixture. That is, adding 30 % CF_3I to a lean ethene/air flame exacerbated the situation. It took a mass fraction of almost 45 % to completely suppress the pressure build-up.

The maximum pressure ratios observed in full-scale live-fire testing of uninhibited propane air mixtures are less than 7:1, and photographic evidence from full-scale dry bay testing suggests that turbulent flame speeds are below 300 m/s (Bennett, 1993). The previous experiments created uninhibited pressure ratios up to 25:1 and quasi-detonation velocities over 1100 m/s. By changing the fuel from ethene to propane, and by adjusting the geometry of the detonation/deflagration tube, the pressure ratio and velocity of the combustion wave can be reduced, allowing determination of whether or not a dangerous over-pressure arises during suppression under conditions that represent more likely threat scenarios.

The specific objectives of the current research project are the following:

a. To determine the effectiveness of HFC-125, relative to FC-218, in suppressing high speed turbulent propane/air flames using the detonation/deflagration tube apparatus.

b. To determine the conditions in the detonation/deflagration tube (equivalence ratio, tube geometry) which lead to excessive pressure build-up during suppression by HFC-125 of propane/air mixtures initially at room temperature and pressure.

c. To determine the effectiveness of CF_3I, relative to FC-218, in suppressing high speed turbulent propane/air flames using the detonation/deflagration tube apparatus.

d. To recommend a ranking of the three agents for full-scale dry bay applications based upon the current and previous suppression experiments.

2.2 Technical Approach and Task Summary

The detonation/deflagration tube is a unique apparatus for evaluating a fire suppressant in a highly dynamic situation. A shock wave precedes the flame, with obstructions in the flow, if any, promoting intense mixing of the fresh reactants with the combustion products and causing the pressure waves to interact with the mixing region. Given enough distance, the initially subsonic flame (deflagration) can accelerate dramatically, reaching the supersonic regime (detonation), and increasing the temperature of the reaction zone behind the shock as well as further adding to the heat release rate. Depending upon the geometric details, the wave can approach its theoretical Chapman-Jouguet velocity and accompanying high pressure ratio. Even a slight variation in composition of the reactants near the limit of detonation can cause a dramatic change in the wave velocity and cause destructive pressures to be attained.

Extensive literature exists describing the kinetics and dynamics of flame/shock wave systems formed within classical detonation tubes (*e.g.*, Lefebvre *et al.*, 1992; Nettleton, 1987; Lee, 1984; Baker *et al.*, 1983; Westbrook, 1982). Chapman and Wheeler (1926) were the first to note that a methane/air flame could be accelerated to a terminal velocity in a shorter distance within a circular tube by placing obstacles into the flow. Lee *et al.* (1984) built on this observation to study quasi-detonations in hydrogen/air and hydrocarbon/air mixtures.

A quasi-detonation propagates more slowly than a true detonation due to pressure losses in the flow, but its structure is more complex than a true detonation, and the mechanism of its propagation is not fully understood. Although obstructed flow is more difficult to analyze than the flow in a smooth-walled tube, the complex obstructed arrangement has been investigated here because it more closely simulates a potentially damaging condition in the dry bay. The present construction of the detonation/deflagration tube facility is designed to compare both obstructed and unobstructed flow conditions.

Because the fire extinguishant is unlikely to be released prior to the establishment of a turbulent flame, the traditional experiment in which the flame inhibitor is premixed with the fuel and air prior to ignition does not replicate the chemistry critical to the actual situation. The NIST facility has been designed to provide a quiescent air/fuel/agent environment into which an uninhibited, fully turbulent flame propagates. The desire to rapidly suppress a flame and the associated pressure build up in such a situation is the primary objective behind this study. An ideal agent would quench the exothermic chemistry at low concentrations and prevent the further build-up of pressure waves; however, the incident mechanical shock can only be reduced through viscous damping, and remains even when the chemistry has been satisfactorily interrupted. Shock/flame wave velocity and pressure ratio were the two dependent parameters that were measured as a means to characterize the extent of flame suppression. The velocity was determined by the time it took for the pressure wave to travel the distance between two pressure transducers. The pressure ratio was evaluated from the average amplitude of the first pressure pulse recorded by each transducer, normalized by the initial pressure.

A number of specific tasks were performed using the detonation/deflagration tube apparatus. First, experiments were conducted to determine the range of Mach numbers and pressure ratios obtainable in the tube using propane rather than ethene. The objective of this task was to produce in a predictable manner high speed turbulent flames (with Mach numbers between 1 and 2 and pressure ratios between 3 and 10) by manipulating the initial conditions in the tube. The variables at our disposal were the propane/air ratio, the fuel partial pressure, and the length of the tube and internal spiral. The conditions which led to repeatable subsonic flames were noted. Next, the pressure ratios and Mach numbers were measured in lean, stoichiometric and rich propane/air mixtures over a range of HFC-125, FC-218 and CF_3I mass fractions in the test section of the tube. The initial conditions were chosen to produce uninhibited Mach numbers below 2.0 and pressure ratios smaller than 10.

2.3 Experimental Set-up

2.3.1 Design. The two-sectional detonation/deflagration tube was designed (Gmurczyk *et al.*, 1993, 1994) to examine the performance of the alternative agents in a highly dynamic situation, in which the pressure effects on the chemistry are thought to be important. Using the detonation/deflagration tube, the effectiveness of a fire fighting agent in suppressing a high speed, premixed flame or quasi-detonation can be rated by the extent to which it decelerates the propagating flame and simultaneously attenuates the hazardous shock which is always ahead of the flame.

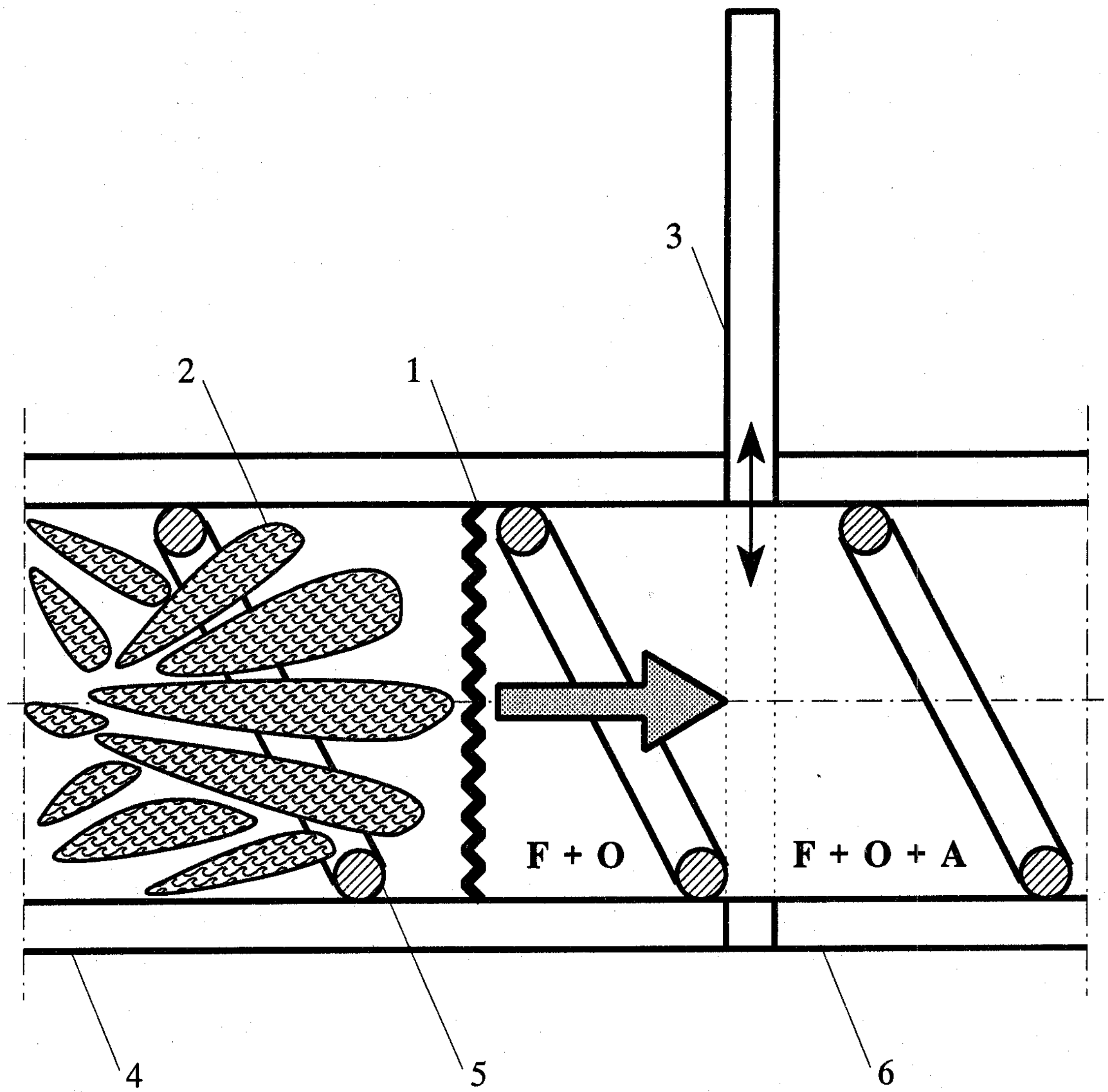
A primary feature of the set-up is that the conditions of the ignition event do not affect the suppression process itself. Also, because an agent of interest is premixed with the fuel and air in a section of the tube separated from the ignition event, the influence of entrainment of the agent into the flame is minimized. The tube is closed to allow the increase in pressure to interact with the combustion chemistry.

The heart of the facility is shown schematically in Figure 1. The left hand side of the picture shows a fragment of the driver section (flame/shock generation region) of the tube separated by a partition from the test section (flame/shock suppression/attenuation region) of the tube on the right hand side of the picture. The flame/shock system propagating within a combustible mixture is fully established before entering the region occupied by a suppressant premixed with the same combustible mixture.

The driver section is 5 m long (see Figure 2) and is equipped at the closed end with a spark plug. This section is filled with the combustible mixture of ethene or propane and air of various compositions. The gas handling system (see Figure 3) consists of a vacuum pumping network; pressurized gas cylinders for the fuel, oxidizer and agent; and a dual circulating pump (Metal Bellows MB 602 XP).[1]

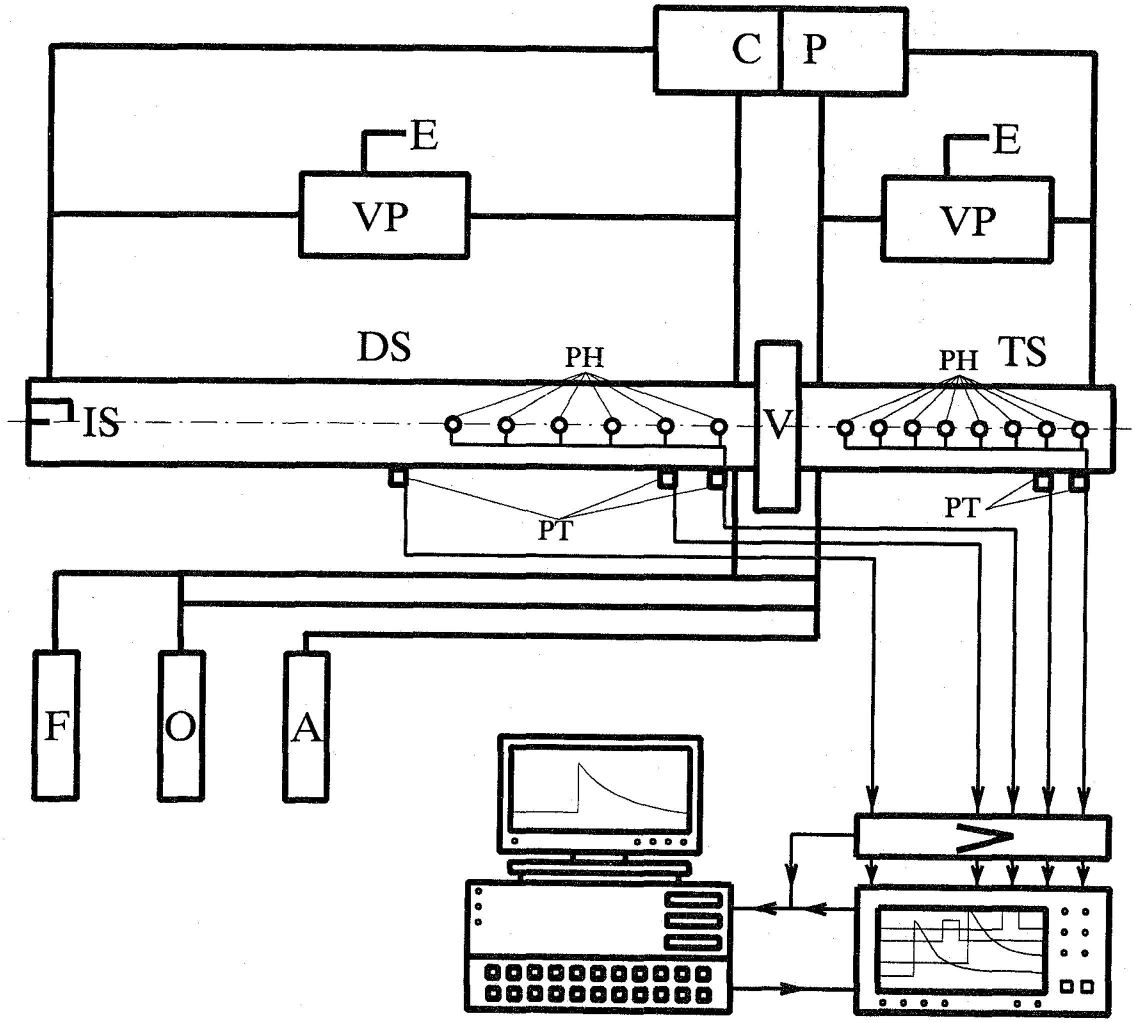
---

[1] Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.



1 - SHOCK WAVE, 2 - TURBULENT FLAME, 3 - GATE VALVE, 4 - DRIVER SECTION, 5 - SPIRAL INSERT, 6 - TEST SECTION, F - FUEL, O - OXIDIZER, A - AGENT

Figure 1. Schematic of the combustion/suppression process in the detonation/deflagration tube.



DS - DRIVER SECTION, TS - TEST SECTION, V - GATE VALVE, IS - IGNITION SYSTEM, CP - CIRCULATION PUMP, VP - VACUUM PUMP, E - EXHAUST, F - FUEL, O - OXIDIZER, A - AGENT, PH - FAST PHOTODIODE, PT - PIEZOELECTRIC PRESSURE TRANSDUCER, > - BLOCK OF AMPLIFIERS

Figure 2. Schematic of the detonation/deflagration tube facility designed and installed at NIST.

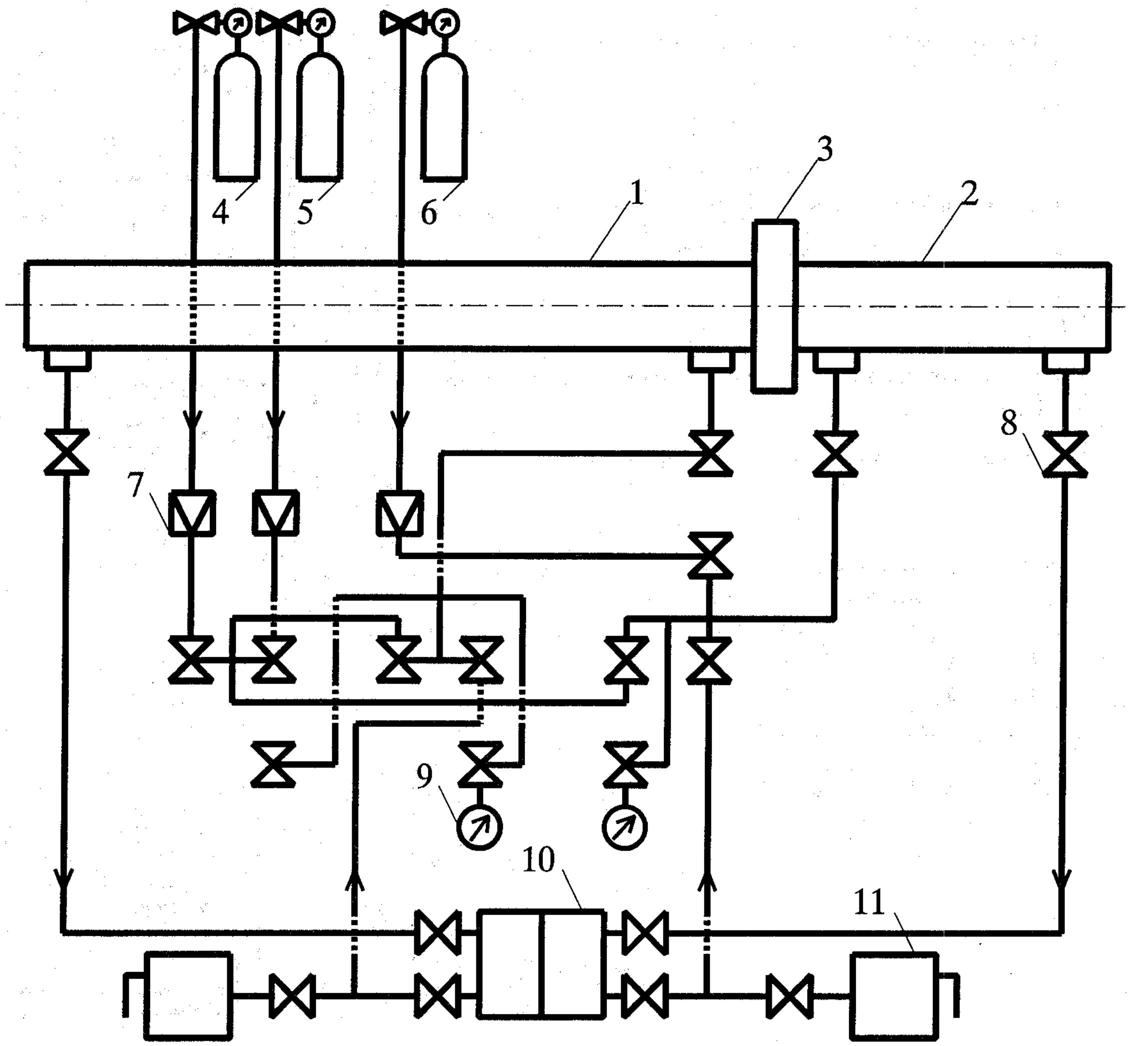


Figure 3. Schematic of the detonation/deflagration tube gas handling system.

The ignition energy is delivered in a micro-explosion of a tin droplet short-circuiting the tips of nichrome electrodes connected to an 80 V power supply. Spiral-shaped obstructions made of 6.4 mm stainless steel rods with a pitch equal to the inner diameter of the tube are inserted into the tube, to produce an area blockage ratio of 44 %, close to the value which is known to promote a high-speed or quasi-detonation regime of combustion.

The second section of the detonation/deflagration tube contained the gaseous agent along with the same fuel/air mixture used in the driver section. The diameter is the same and its length is either 2.5 m or 5.0 m. The flame and shock signals serving to determine velocities and pressures were taken 2.2 m downstream behind the gate valve when the 2.5 m long test section of the tube was installed. The 5 m test section was used without the spiral insert. The additional length was used to eliminate the reflected shock wave that sometimes interfered with a slower moving primary reaction front. The flame signals serving to determine velocities in the long tube were taken close to the entrance region of the test section, 0.3 m downstream behind the gate valve, to better ascertain the immediate impact of the inhibitors on the flame dynamics; the shock signals were measured 2.2 m into the test section, which is the same location used for the short tube.

The driver and test sections are separated from each other by a 50 mm inner diameter, stainless steel, gate valve (MDC model GV-2000M-SP), which remains closed until just before ignition. Kistler model 603B1 dynamic piezoelectric pressure transducers (with dual mode charge amplifiers model 5010A10) and Siemens model BPX 65 silicon planar PIN high speed photodiodes are located along the test section to monitor the strength and speed of the combustion wave. Refer to Figures 4, 5, and 6. Their output was recorded either with a 50 MHz IBM Personal Computer with 32 bit EISA data acquisition board or with a fast, multi-channel, digital storage oscilloscope (Le Croy model 9314 M). In the latter case the data were also stored in the computer, since full communication was possible.

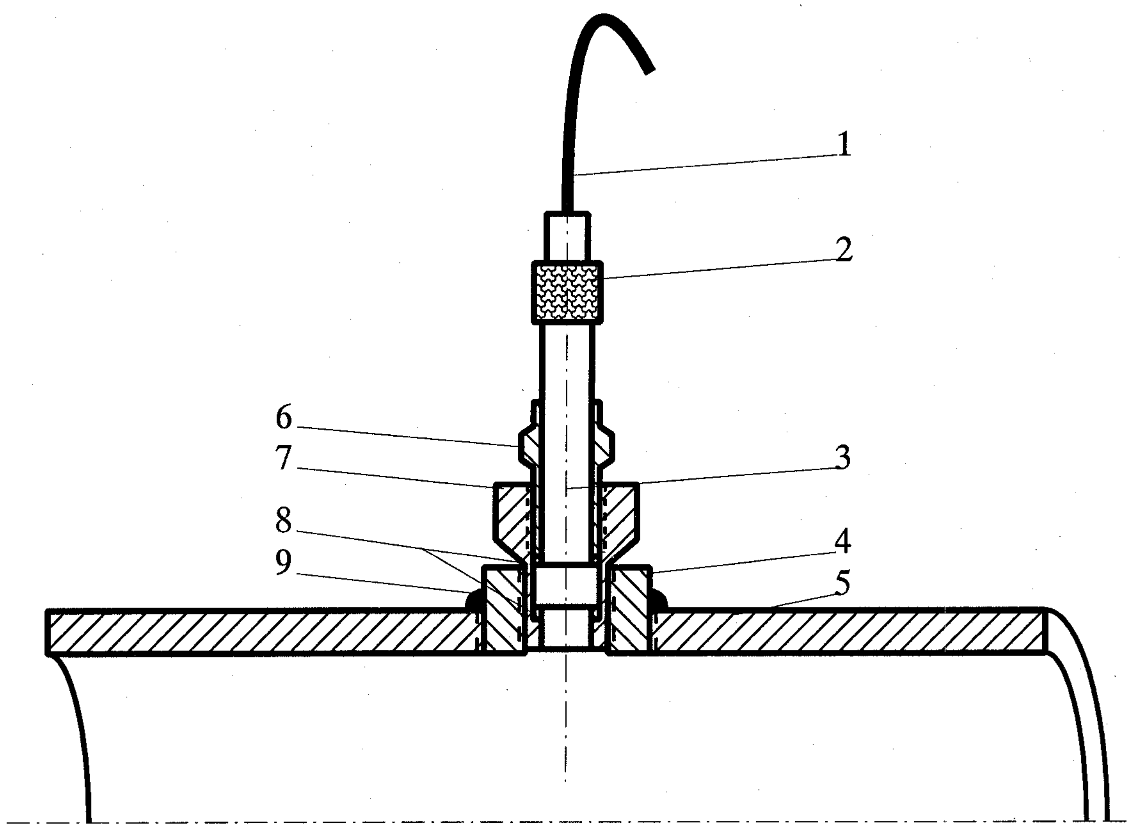
2.3.2 Operation. The whole system is evacuated to 10^{-1} Pa before filling the two sections separately with the desired mixtures, which are attained through the method of static partial pressures measured with Omega PX811 high accuracy absolute pressure gauges. The fuel/air ratio and total pressures are held constant across the gate valve. After filling, the gases are homogenized independently using a double, spark-free circulating pump, recirculating the entire tube volume a total of 20 times. The mixtures are then left for five minutes to become quiescent. About 10 s prior to ignition, the gate valve is opened manually. After ignition, the flame propagates into the driver section and accelerates quickly due to the intense turbulence created by the interactions of the flow with the obstacles. This generates a shock wave ahead of the flame. After passing through the open gate valve the flame/shock system encounters the same combustible mixture and a certain amount of agent in the test section. Depending on the concentration of the agent, the flame may be extinguished (or enhanced) and the pressure wave may be attenuated (or amplified).

2.4 Experimental Results

2.4.1 Conditions. The following independent parameters were changed during the course of the experiments:

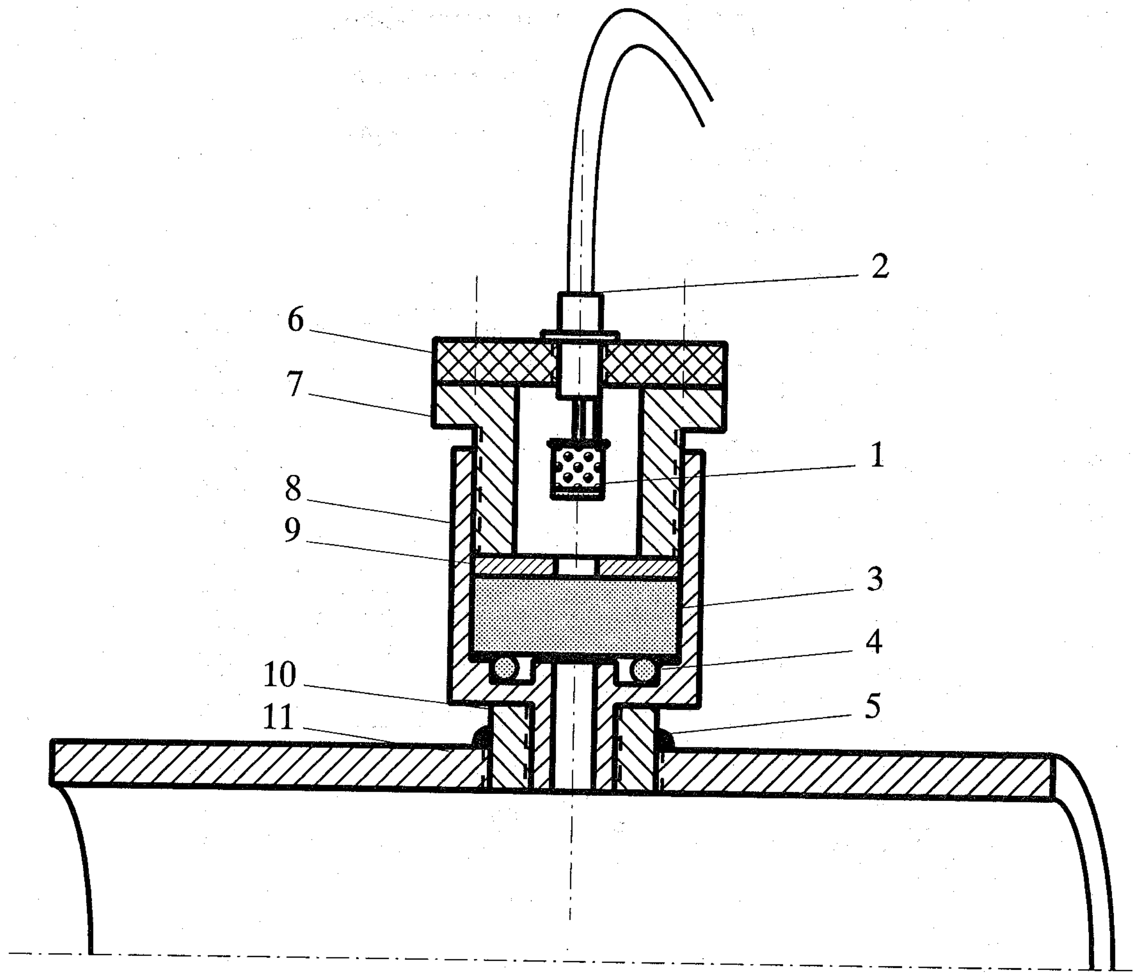
- type of suppressant (C_2HF_5, C_3F_8, and CF_3I);

- concentration of suppressant;



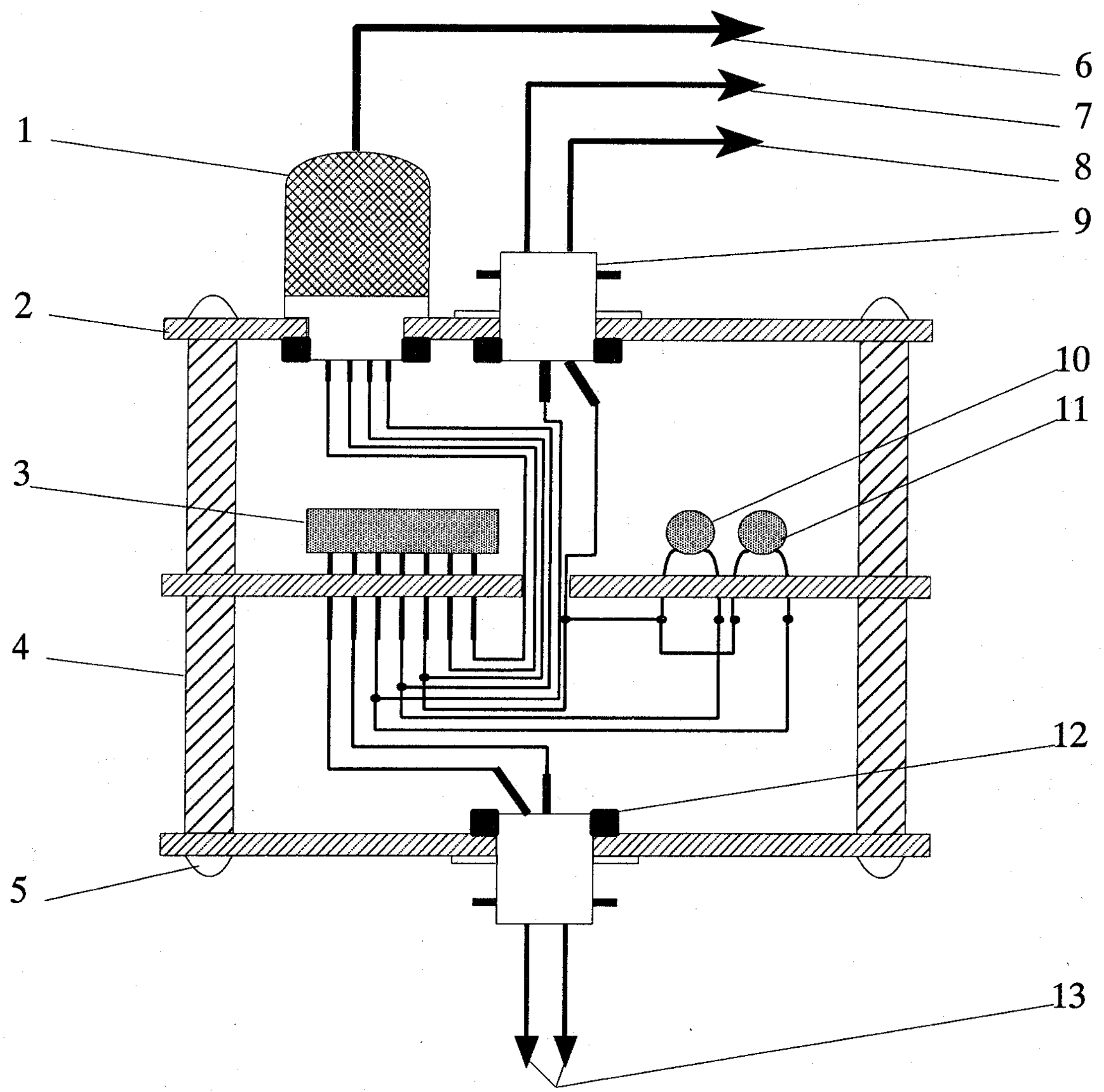
1 - LOW-NOISE CABLE, 2 - CABLE CONNECTOR, 3 - PIEZO-ELECTRIC PRESSURE TRANSDUCER, 4 - STUB, 5 - TUBE, 6 - RETAINING NUT, 7 - HOLDER, 8 - SEALS, 9 - SEAL WELD

Figure 4. Schematic of the piezoelectric dynamic pressure transducer mounting.



1 - PHOTODIODE, 2 - BNC CABLE, 3 - QUARTZ WINDOW,
4 - "O" RING, 5 - SEAL WELD, 6 - COVER, 7 - BUSH, 8 - CASE
9 - WASHER, 10 - STUB, 11 - TUBE

Figure 5. Schematic of the fast photodiode mounting.



1 - DIN CONNECTOR, 2 - CIRCUIT BOARD, 3 - OPERATIOANL AMPLIFIER, 4 - STANDOFF, 5 - SCREW, 6 - TO POWER SUPPLY, 7 - SIGNAL OUTPUT, 8 - GROUND, 9 - BNC CONNECTOR, 10, 11 - CAPACITORS, 12 - NUT, 13 - TO PHOTODIODE

Figure 6. Schematic of the fast photodiode amplifier.

- type of fuel (ethene or propane);

- equivalence ratio of the combustible mixture (lean, stoichiometric, rich)

- geometry of the tube (2.5 m or 5 m long test section, with or without spiral).

The initial temperature of the mixtures was ambient (22 °C ± 3 °C) and the initial pressure was 100± 0.6 kPa. The oxidizer used in all experiments was breathing grade air. Ethene and propane (CP grade 99.5 % volume purity) were chosen as the fuels; ethene because it is known that detonations can be obtained in a tube of this geometry simply by varying the stoichiometry, and propane because it more closely resembles a jet fuel and can reproduce turbulent flames with pressure ratios under 10:1 and wave speeds down to sonic conditions. The extinguishing compounds were used as supplied by the manufacturers.

The partial pressure measurements were affected by the uncertainty of the static pressure transducer (± 0.3 kPa maximum uncertainty after combining non-linearity, hysteresis, repeatability, and temperature effects), the uncertainty of the digital display device (± 0.015 kPa), the uncertainty associated with the purity of the gases (± 0.5 % of partial pressure reading), and the uncertainty associated with possible gas losses in the circulation pump (up to 0.3 % of the partial pressure reading, in the worst case). Assuming that the errors were directly additive, the partial pressure for any component in the mixture was uncertain to less than 0.32 kPa plus 0.3 % of the reading.

2.4.2 Measurement Signals. Figure 7 shows representative signals coming from two fast photodiodes which indicate the presence of radiation (peak response at 850 nm) associated with the reaction front traveling in the tube. Figure 8 displays signals from two piezoelectric pressure transducers which represent a pressure jump associated with the shock wave ahead of the primary reaction zone. The time difference between the occurrence of the signals allows one to determine flame and shock velocities. The amplitude of the pressure signals permits determination of the pressure ratio of the shock.

The uncertainty of the determination of the shock wave amplitude was affected by the combined uncertainty of the dynamic pressure transducer (± 1 % of the reading), the combined uncertainty of the transducer amplifiers (± 0.5 % of the reading), the combined uncertainty of the digital data acquisition system (± 0.5 %), and the combined uncertainty of the digital readout device (± 0.2 %). Assuming additivity of errors, the resultant accuracy of determining the shock wave amplitude is ± 2.2 %. The uncertainty of the determination of the shock time differences was affected by the same elements, as well as the transducer rise time (< 2 μs). The shock speed can thereby be estimated to be uncertain to less than ± 4.4 % of the reported reading (accounting for the differential nature of this measurement). The uncertainty of the determination of the flame travel time was affected primarily by the rise time of the photodiode, which is 30 ns. The combined uncertainty of the magnitude of the photodiode signal is estimated to be ± 2 % of the range.

2.4.3 Combustion Characteristics. The combustion generated in the driver section creates a shock wave followed by a chemically reacting region. The dependent parameters that were used to characterize the combustion within the test section of the tube are the pressure rise across the shock, the speed of the shock, and the speed of the chemically reacting radiation front. A secondary reaction was sometimes observed following the reflection of the incident shock wave from the end wall. The incident (or forward-travelling) shock wave speed and pressure ratio were determined from the

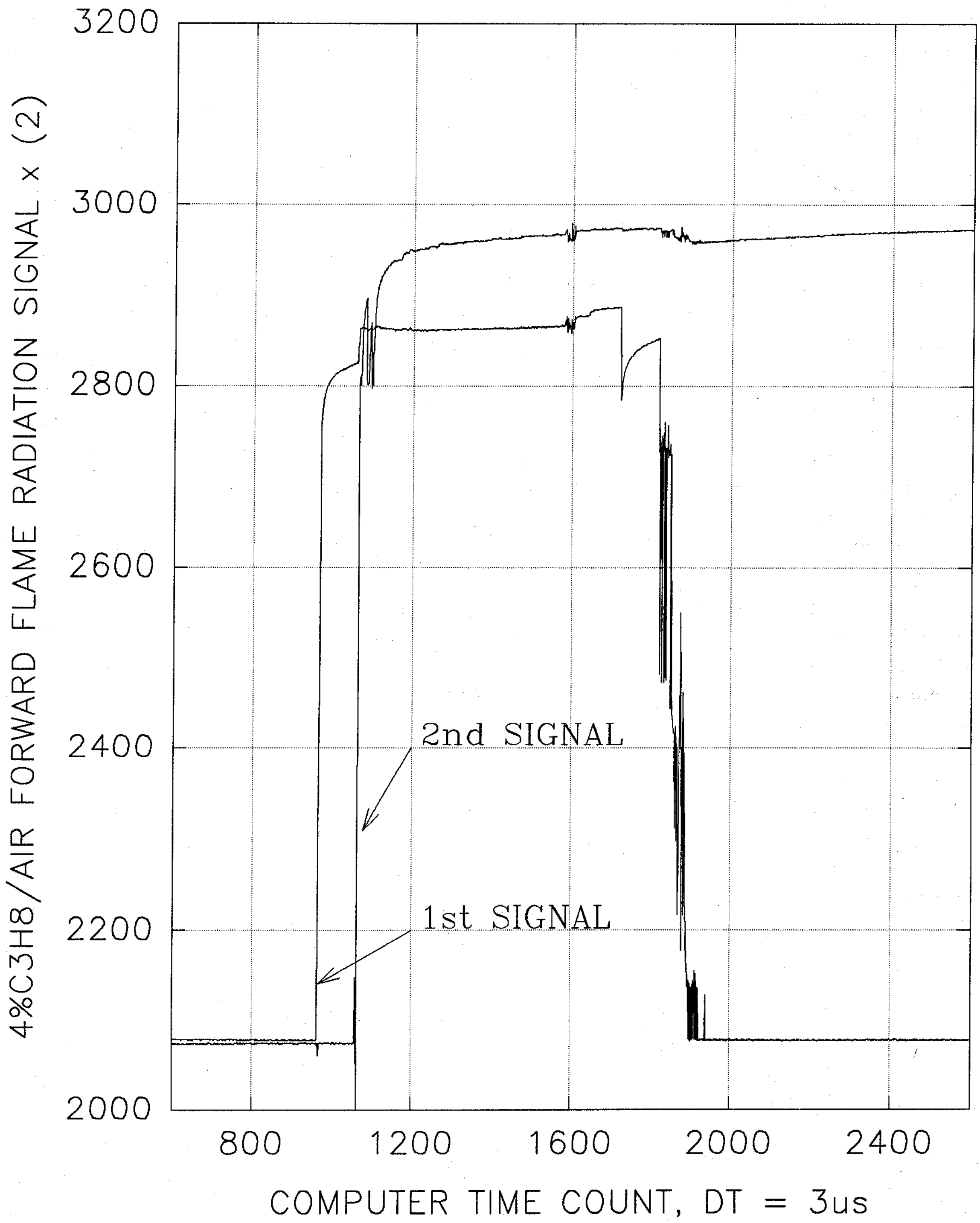


Figure 7. Typical measurement signals representing flame radiation detected by the photodiodes.

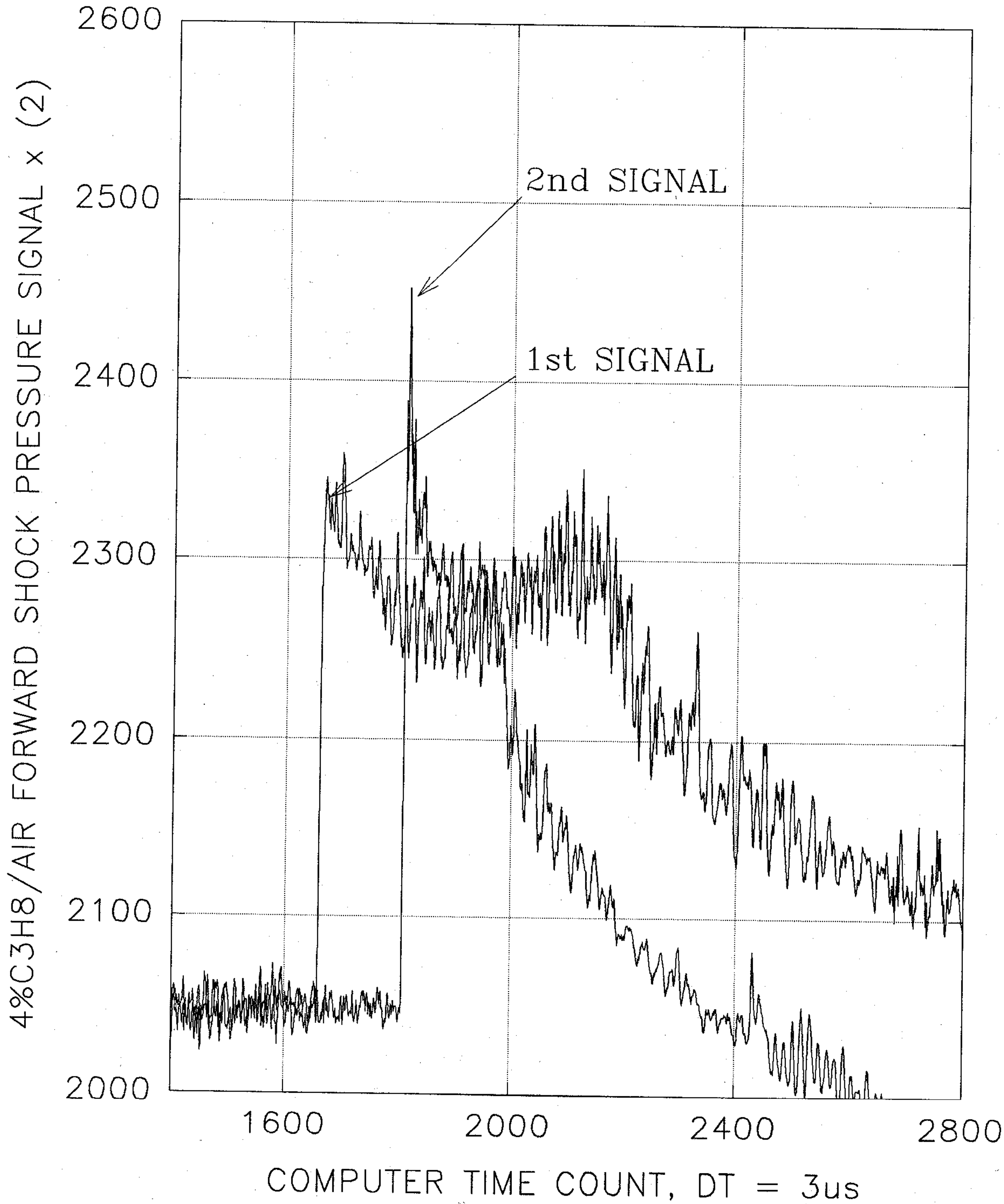


Figure 8. Typical measurement signals representing shock pressure detected by the dynamic pressure transducers.

piezoelectric transducer signals, and the time between activation of the photodiodes was used to calculate the forward-travelling radiation (or flame) front.

The repeatability of the measurements was affected by the following factors: preparation of the mixtures; circulation/homogenization of the mixtures; opening of the gate valve; the ignition parameters; formation/propagation of the flame/shock; vibrations of the spiral insert; and ambient temperature changes (ambient air pressure and humidity changes did not affect the results as air was supplied from a gas cylinder). Because each of these factors has an indeterminate randomness associated with it, a single test condition was repeated eleven times to quantify the precision of the experiment: a lean mixture of propane and air, with no suppressant, and the 10 m long tube with no spiral in the test section. More than twenty replicates would have been required to produce a meaningful standard deviation as specified by Taylor and Kuyatt (1994); thus, in the present study the maximum, rather than standard, deviation is used to indicate the precision of the inferred results. The mean of the eleven tests and maximum absolute deviations are as follows: flame speed, 334 m/s ± 38 m/s; shock speed, 681 m/s ± 25 m/s; and shock pressure ratio, 8.16 ± 0.38.

2.4.3.1 Ethene/Air Mixtures. Figure 9 shows the dependence of the forward shock wave velocity versus equivalence ratio of the ethene/air mixture for the cases with and without the spiral insert in the 2.5 m test section. The equivalence ratio was changed to cover the full range of various combustion/flammability modes detectable by the installed apparatus. The shock wave generated by an accelerating flame is detectable for equivalence ratios between 0.5 and 2.12 for the two geometric configurations. The maximum shock velocity of nearly 2000 m/s was recorded for a rich mixture with the spiral absent. Except for the extreme lean and rich cases, with shock velocities less than 500 m/s, the flame was intimate with the shock.

Figure 10 displays the respective forward shock pressure ratios in the ethene/air mixture versus equivalence ratio for the two geometric configurations. Interestingly, the maximum pressure ratio of 35 was recorded for the situation with the spiral, which indicates clearly that transverse shock reflections from the wall play an important role in the whole process. However, in general, the shape of the pressure ratio curves corresponds well with the shape of the velocity curves.

There are four modes of combustion observed in the detonation/deflagration facility:

a. Low-speed deflagration: generates a weak pressure wave in which the flame front is uncoupled. A typical pressure wave velocity is 400 m/s and pressure ratio is 1.5 for the two geometric configurations.

b. High-speed deflagration: generates a strong pressure wave that is coupled with the flame front, the velocity of the flame is the same as the velocity of the pressure wave, and the shock-flame distance is on the order of centimeters. A typical velocity is 800 m/s and pressure ratio is 16 for the lean mixtures, and 1400 m/s and 20 for the rich mixtures, respectively, when the spiral insert is in the tube. When the spiral is not present in the tube the respective parameters are as follows: 700 m/s and 7 for the lean mixtures, and 600 m/s and 3 for the rich mixtures.

c. Quasi-detonation: associated with the occurrence of high velocities and pressure ratios. The flame front is coupled with the pressure wave, the velocity of the flame is the same as the velocity of the pressure wave, and the shock-flame distance is on the order of millimeters. Typical velocities are 1200 m/s to 1500 m/s and pressure ratios are 20 to 35 over broad lean and rich ranges for the situation with the spiral insert in place. When the spiral is not present the transition from the high-speed deflagration mode to a detonation is gradual. The velocities

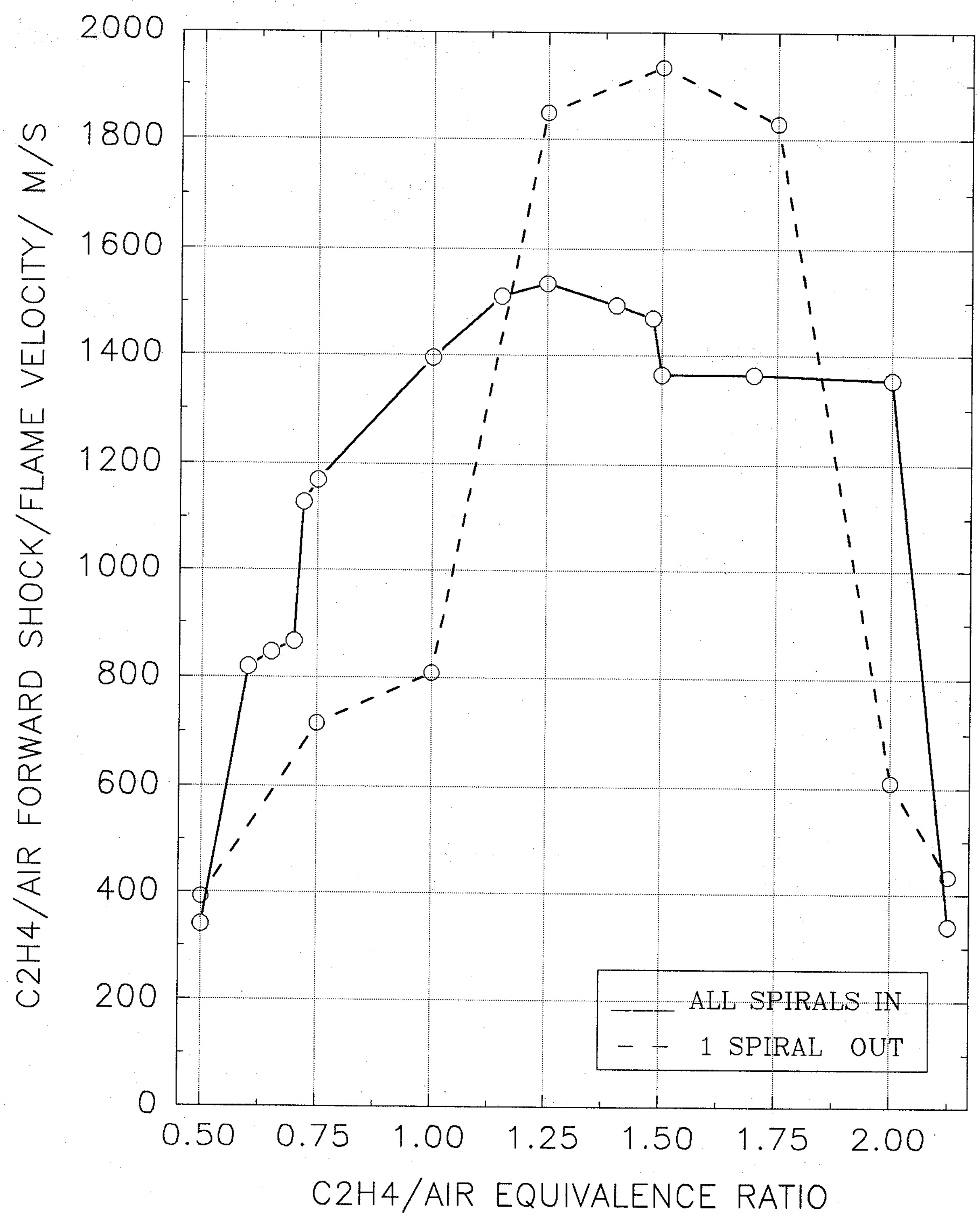


Figure 9. Combustion modes in the ethene/air mixtures - shock/flame velocities (2.5 m test section).

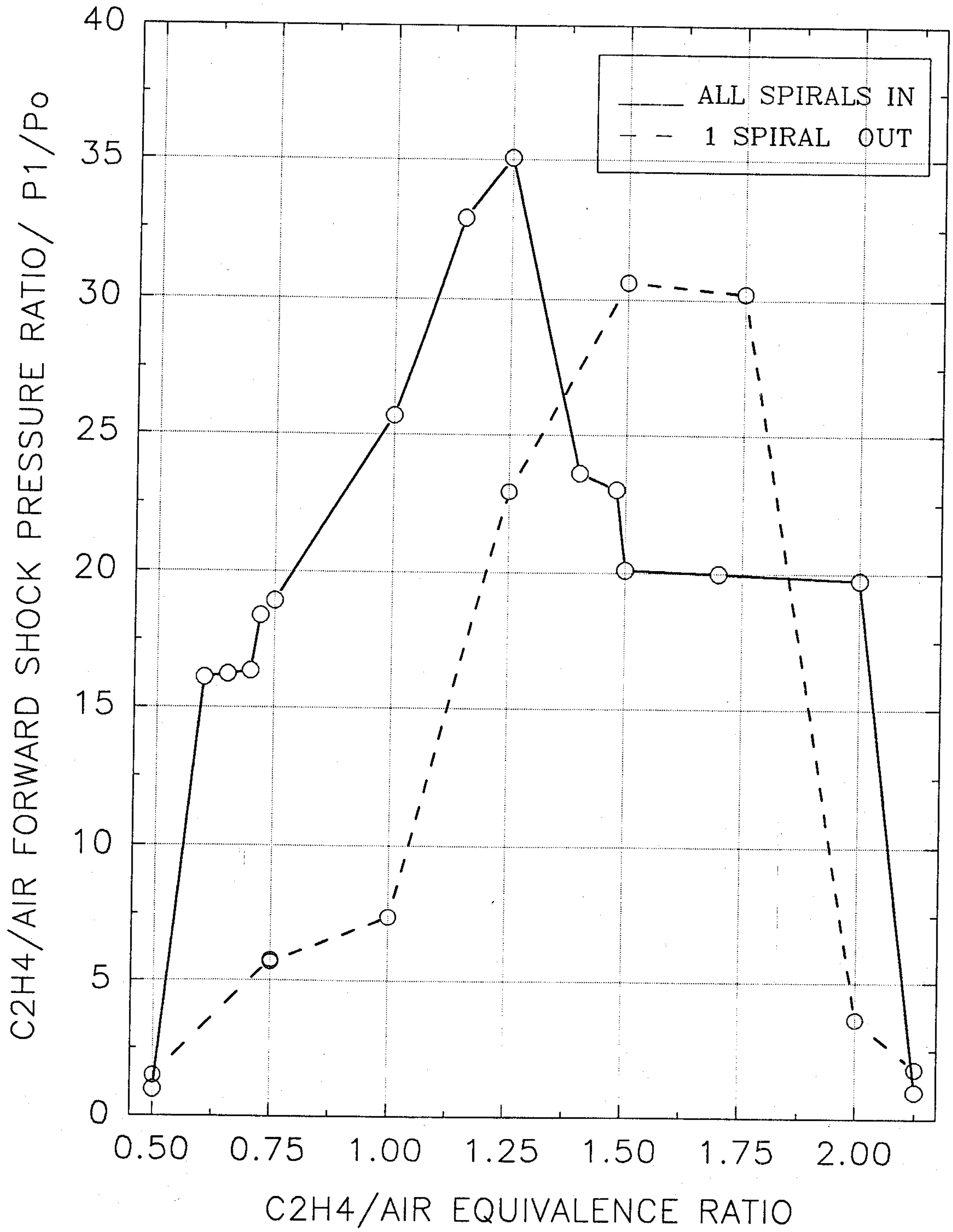


Figure 10. Combustion modes in the ethene/air mixtures - shock pressure ratios (2.5 m test section).

and pressure ratios are significantly lower. This mode occurs on the rich side of the ethene/air mixture.

d. Chapman-Jouguet detonation: occurs only in the rich ethene/air mixture without the spiral insert. The flame front is coupled with the pressure wave, the velocity of the flame is the same as the velocity of the pressure wave, and the shock-flame distance is undetectable. A typical velocity is 1900 m/s and pressure ratio is 30. The velocity corresponds to the theoretical equilibrium thermodynamic estimates; however, the pressure ratios are 1/3 higher, which may indicate the occurrence of an over-driven detonation mode.

2.4.3.2 Propane/Air Mixtures. Uninhibited propane/air mixtures were evaluated in the 2.5 m test section as well, with and without the spiral insert in the test section. Figure 11 shows the dependence of the forward shock wave velocity on equivalence ratio. The shock wave generated by the accelerating flame was detectable for equivalence ratios between 0.65 and 1.45, both with the spiral present and absent. The maximum shock velocity of about 1300 m/s was recorded for the stoichiometric case with the spiral in place, much less than was found in the ethene/air mixture. The flame velocity was the same as the shock velocity for wave speeds above 800 m/s. This means that the propane generated reaction front can be more easily decoupled from the shock wave than in the ethene/air mixture. Figure 12 displays the respective forward shock pressure ratios in the propane/air mixture versus equivalence ratio. Here the maximum pressure ratio of 27 corresponds to the maximum velocity for the situation with the spiral. In general, the shape of the pressure ratio curves corresponds closely to the shape of the velocity curves.

Three of the four combustion modes observed with the ethene/air experiments were identified when propane was the fuel: low-speed deflagration, high-speed deflagration, and quasi-detonation. The Chapman-Jouguet condition was not observed, and when the spiral was not present in the test section, the quasi-detonation regime of combustion disappeared. There are other differences between the two fuels, as well. The combustion modes at higher velocities overlap totally in the ethene/air mixture for the cases with and without the spiral, while the propane/air mixture is characterized by a clear separation between the combustion modes for the two arrangements. Also, the regime of equivalence ratios for which combustion is detectable in the tube is much broader for the ethene/air mixture. Furthermore, the detonation process is unable to develop in the propane/air mixture when the spiral insert is missing from the tube. However, it is noteworthy that for the first time a quasi-detonation in a propane/air mixture has been recorded in the presence of the spiral obstacle. This finding extends the results of Lee (1984) and Peraldi *et al.* (1986).

2.4.4 Suppression Characteristics. The performance of the three extinguishing compounds (C_2HF_5, C_3F_8, and CF_3I) are analyzed by comparing the velocity and pressure ratio suppression characteristics in the lean, stoichiometric, and rich ethene/air and propane/air mixtures, with and without the presence of obstacles in the test section. (Note: the spiral inserts are always present in the driver section.) Pure nitrogen was placed in the test section as a benchmark to compare its performance to the above alternatives. The fully nitrogen-suppressed pressure ratios, shock speeds and combustion wave speeds are compared to the totally uninhibited fuel/air mixtures in Table 1.

In the ethene/air mixtures, as one might expect, the flame velocity is zero when the test section is filled with N_2, but only under lean and stoichiometric conditions. In the rich mixture the velocity is slightly higher than zero. This means that the residual flame from the driver section of the tube enters the suppression section, since the flame velocity was measured just behind the gate valve separating the two sections of the tube. The respective forward shock velocities decrease because of

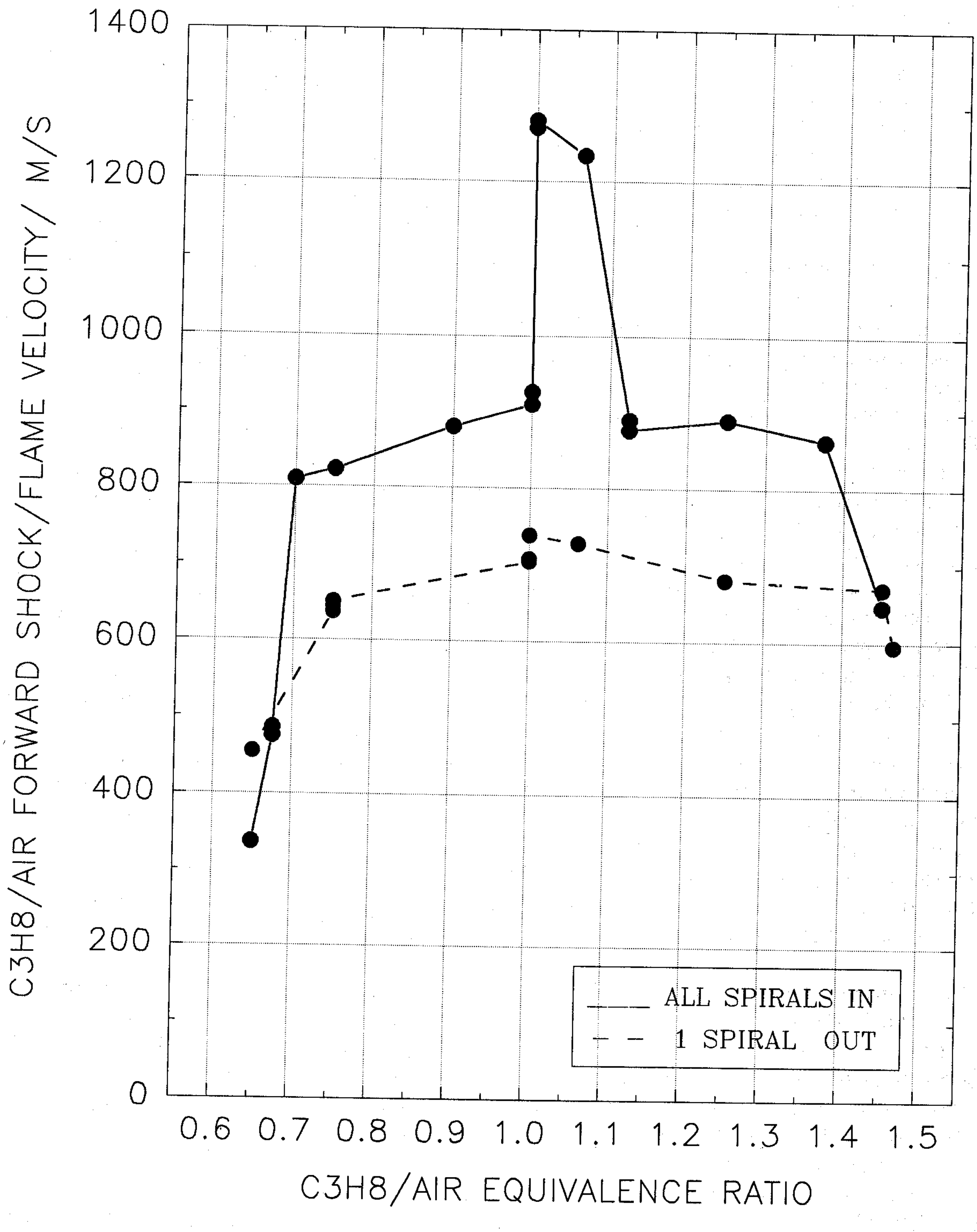


Figure 11. Combustion modes in the propane/air mixtures - shock/flame velocities (2.5 m test section).

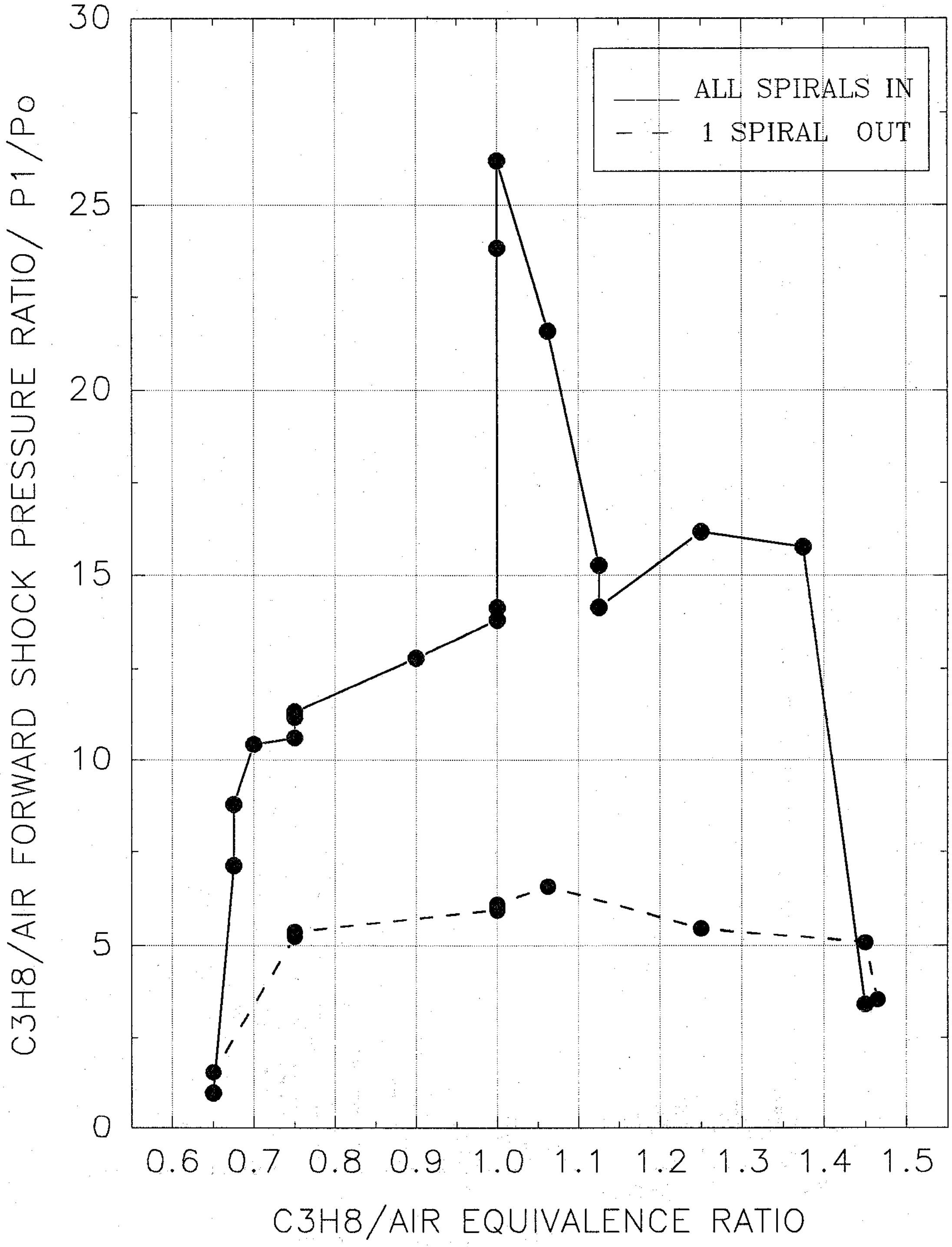


Figure 12. Combustion modes in the propane/air mixtures - shock pressure ratios (2.5 m test section).

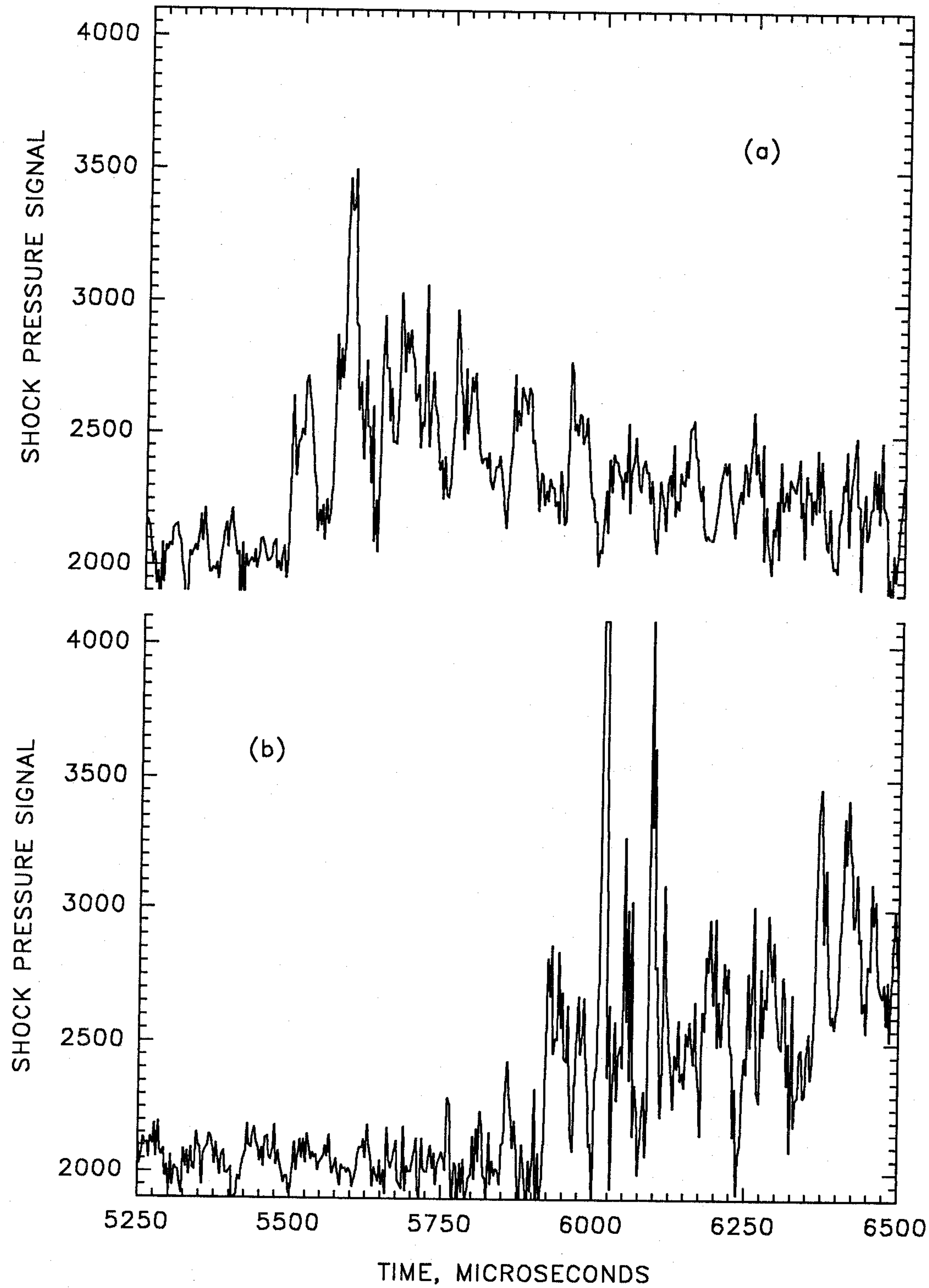


Figure 13. Pressure traces taken in CF_3I-inhibited C_3H_8/air mixture (a) 2.04 m into test section, and (b) 2.37 m into test section.

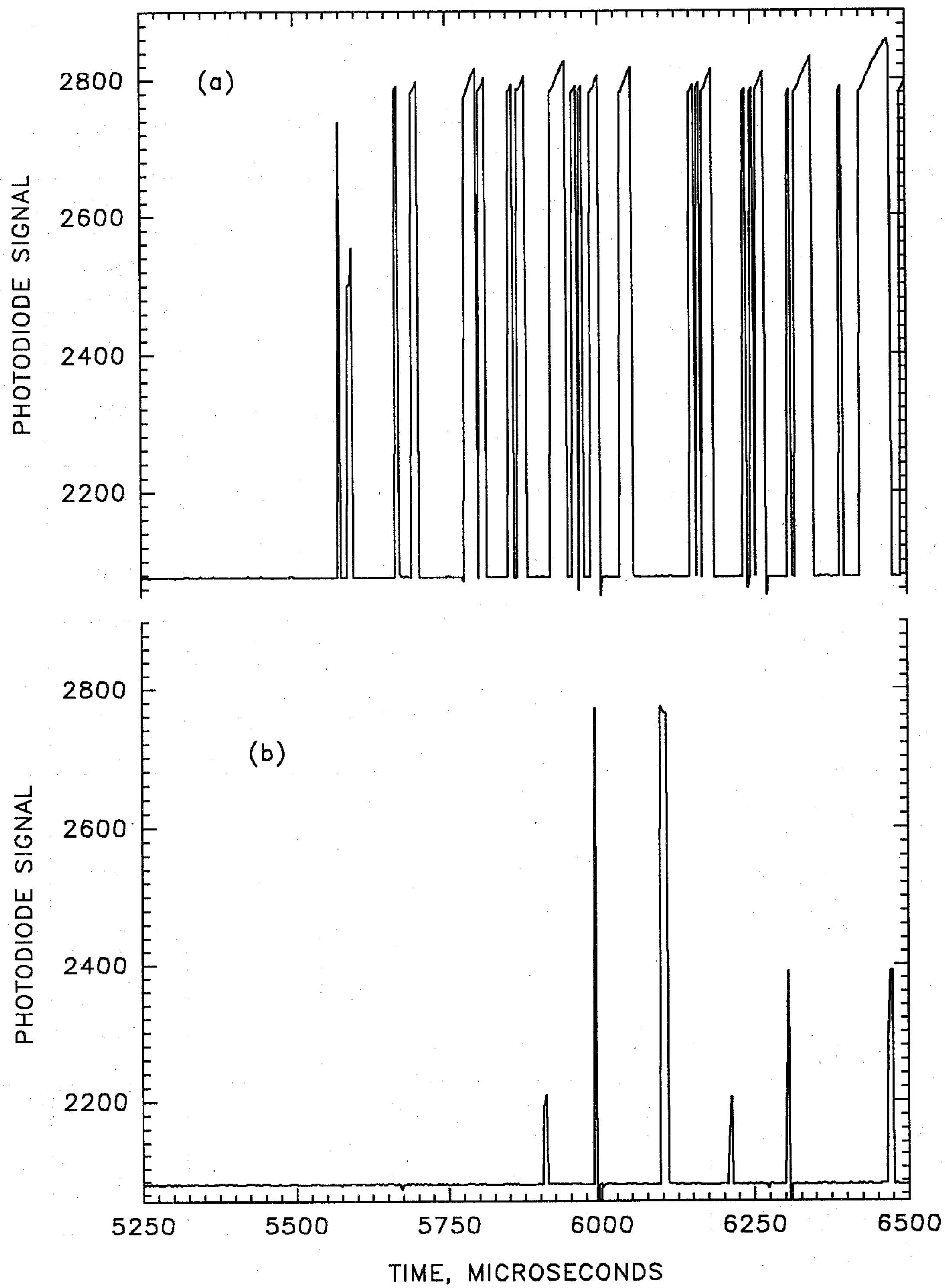


Figure 14. Photodiode signals from CF_3I-inhibited C_3H_8/air mixture, taken (a) 2.04 m into test section, and (b) 2.37 m into test section.

Table 1. Pressure ratios, shock speeds and combustion wave speeds comparing fully suppressed (100% N_2) to totally unsuppressed (0% N_2) test conditions

Fuel Mixture	Test Section	0% Nitrogen			100% Nitrogen		
		P_1/P_0	V_{shock} (m/s)	V_{comb} (m/s)	P_1/P_0	V_{shock} (m/s)	V_{comb} (m/s)
C_2H_4, Φ=0.75	2.5 m (spiral)	18	1170	1170	2.5	440	0
	5.0 m (no spiral)	6.2	710	600	4.1	600	0
C_2H_4, Φ=1.00	2.5 m (spiral)	26	1400	1400	3.5	450	0
	5.0 m (no spiral)	6.5	720	720	4.7	660	0
C_2H_4, Φ=1.25	2.5 m (spiral)	35	1530	1530	*	*	*
	5.0 m (no spiral)	11	940	930	5.0	730	20
C_3H_8, Φ=0.86	2.5 m (spiral)	11	815	815	*	*	*
	5.0 m (no spiral)	8.1	690	330	4.5	575	103
C_3H_8, Φ=1.00	2.5 m (spiral)	13.5	900	900	*	*	*
	5.0 m (no spiral)	8.8	695	620	4.7	619	105
C_3H_8, Φ=1.25	2.5 m (spiral)	16	890	890	*	*	*
	5.0 m (no spiral)	8.3	690	510	4.5	586	45

* no data available

the disappearance of the energy supplied by exothermic chemical reactions, and the forward shock pressure ratios drop most significantly when the spiral is present.

In the propane/air mixtures, in every case the flame velocity is higher than zero, which means that 100 % nitrogen cannot fully extinguish the flame in the propane/air mixtures within a short distance. When compared to the flame propagating in the ethene/air mixtures, the initial velocity in nitrogen is lower but it is more stable on contact with an inert environment. The respective forward shock velocities in the propane/air mixtures are approximately proportional to the initial shock velocities established in the driver section of the tube. The respective forward shock pressure ratios at the three equivalence ratios correspond well to the relative behavior of the shock velocities.

The interaction of the combustion wave with the inhibited fuel/air mixture is a dynamic process which does not reach a steady state within the test section. Figure 13 shows two pressure traces taken 0.33 m apart in a CF_3I inhibited propane/air mixture. The photodiode measurements taken at the same two locations are shown in Figure 14. The initial and peak pressures can be seen to increase with the distance that the wave travels, indicating that the CF_3I is promoting the development of the shock wave. The flame radiation, on the other hand, diminishes as the combustion wave travels from the 2.04 m to 2.37 m position. The on-off behavior of the photodiodes also suggests that the combustion zone is thick and highly nonuniform in intensity.

The suppression data presented in this section have been measured at two different locations, depending upon the configuration. The pressure transducers and photodiodes were mounted 2.04 m and 2.37 m beyond the gate valve in the 2.5 m test section (with the spiral); in the 5.0 m test section (without spiral) the photodiodes were moved to locations 0.21 m and 0.38 m after the gate valve, while the pressure transducers remained at the 2.04 m and 2.37 m locations.

2.4.4.1 C_2HF_5 Performance. The primary motivation for conducting more research in the detonation/deflagration tube is shown in Figure 15. The data for the lean C_2H_4/air mixture in the 2.5 m test section containing the spiral insert was collected in the earlier NIST study (Grosshandler *et al.*, 1994). The shock pressure ratio reaches a maximum of 37:1 for a 6 % mixture of C_2HF_5. This is more than double the pressure increase had no suppressant been added, clearly an untenable situation were it to occur in a dry bay.

The tube geometry and fuel were altered to reduce the severity of the initial conditions to determine the impact on the combustion dynamics. The data points indicated by triangles in Figure 15 were taken with no spiral insert in the 5.0 m long test section. The initial shock pressure ratio is reduced by a factor of 3, and remains below 9:1 out to a partial pressure fraction of 10 %. The sensitivity of the C_2HF_5/C_2H_4/air mixture to small perturbations in the detonation/deflagration tube became apparent when the 6 % experiment was repeated and resulted in a detonation. Except for that one case, removing the spiral greatly reduced the severity of the combustion wave.

Removing the spiral has a similar effect on the shock/combustion wave speed, plotted in Figure 16. The combustion process is completely extinguished when the C_2HF_5 partial pressure reaches 10 %, as compared to about 15 % when the spiral is present in the test section.

Ethene is known to be highly reactive (which is one reason it was selected for the previous study), but it is less representative of a vaporized jet fuel than propane. The original experiments were repeated with C_3H_8 instead of C_2H_4, and these are also plotted (filled circles) in Figures 15 and 16. The C_3H_8 mixture produces significantly lower pressure ratios, never exceeding 15:1 when the spiral is present. The initial shock/combustion wave speed is cut in half by the change in fuel, and the flame radiation is fully extinguished at partial pressure fractions about 4 % lower.

The equivalence ratio of the C_2H_4/air mixture was varied from lean to rich in the obstructed tube. The pressure increase across the shock wave is plotted in Figure 17 as a function of the partial pressure fraction of C_2HF_5 added to the test section. When the equivalence ratio is increased to Φ=1.0

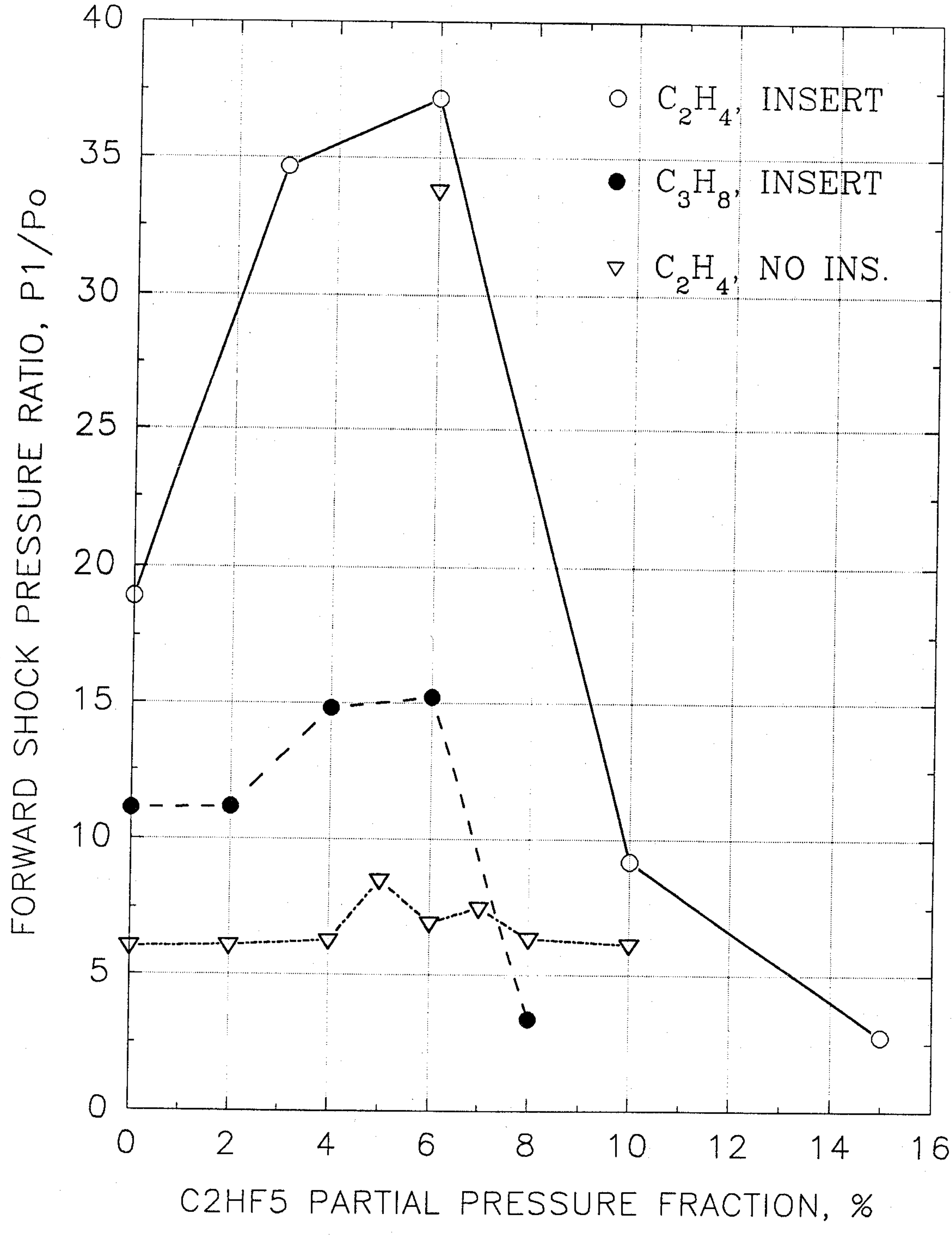


Figure 15. Shock pressure ratio in lean, C_2HF_5-inhibited hydrocarbon/air mixtures, showing impact of spiral insert and fuel-type on suppression process.

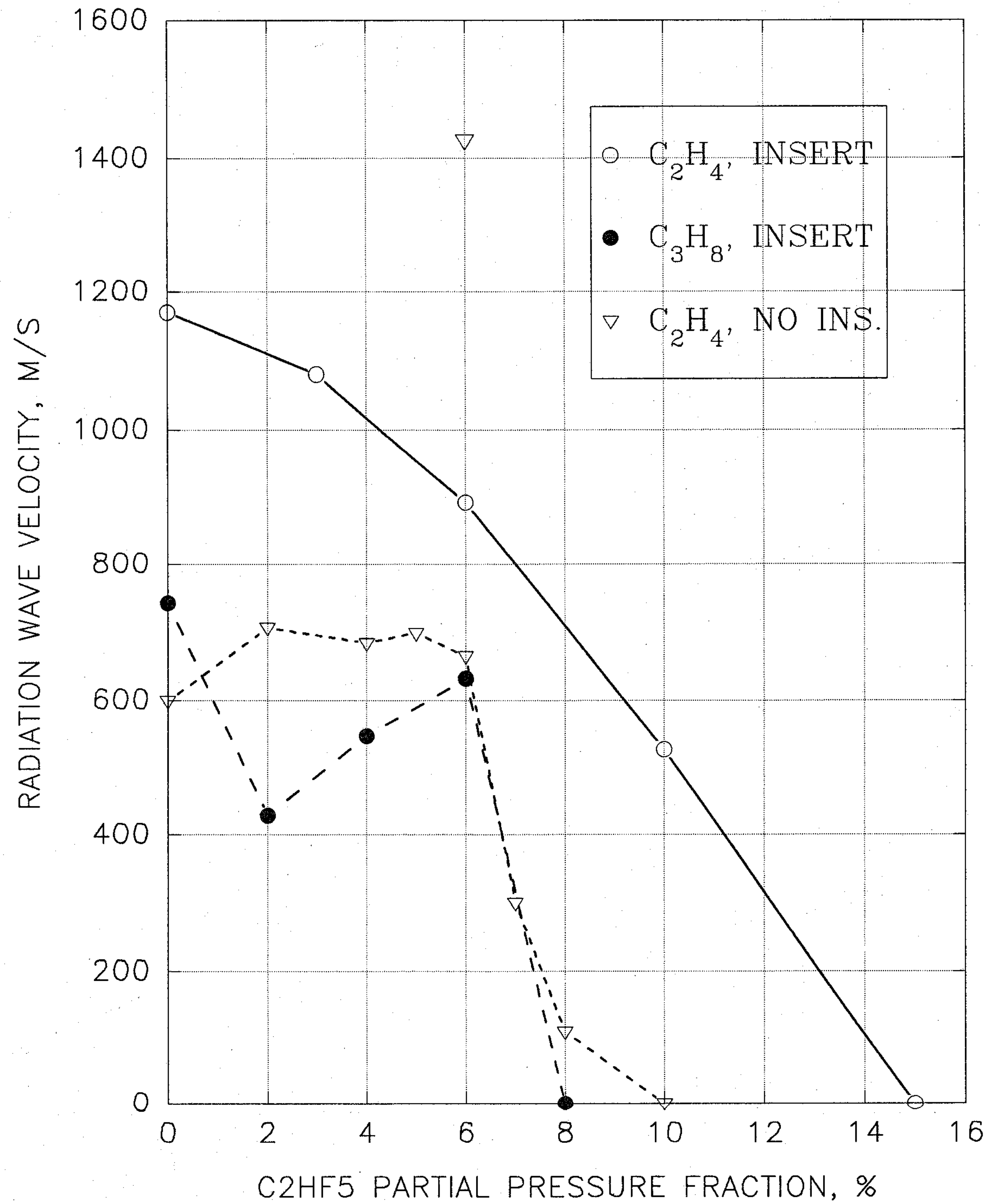


Figure 16. Shock/combustion wave speed in lean, C_2HF_5-inhibited hydrocarbon/air mixtures showing the impact of spiral insert and fuel-type on suppression behavior.

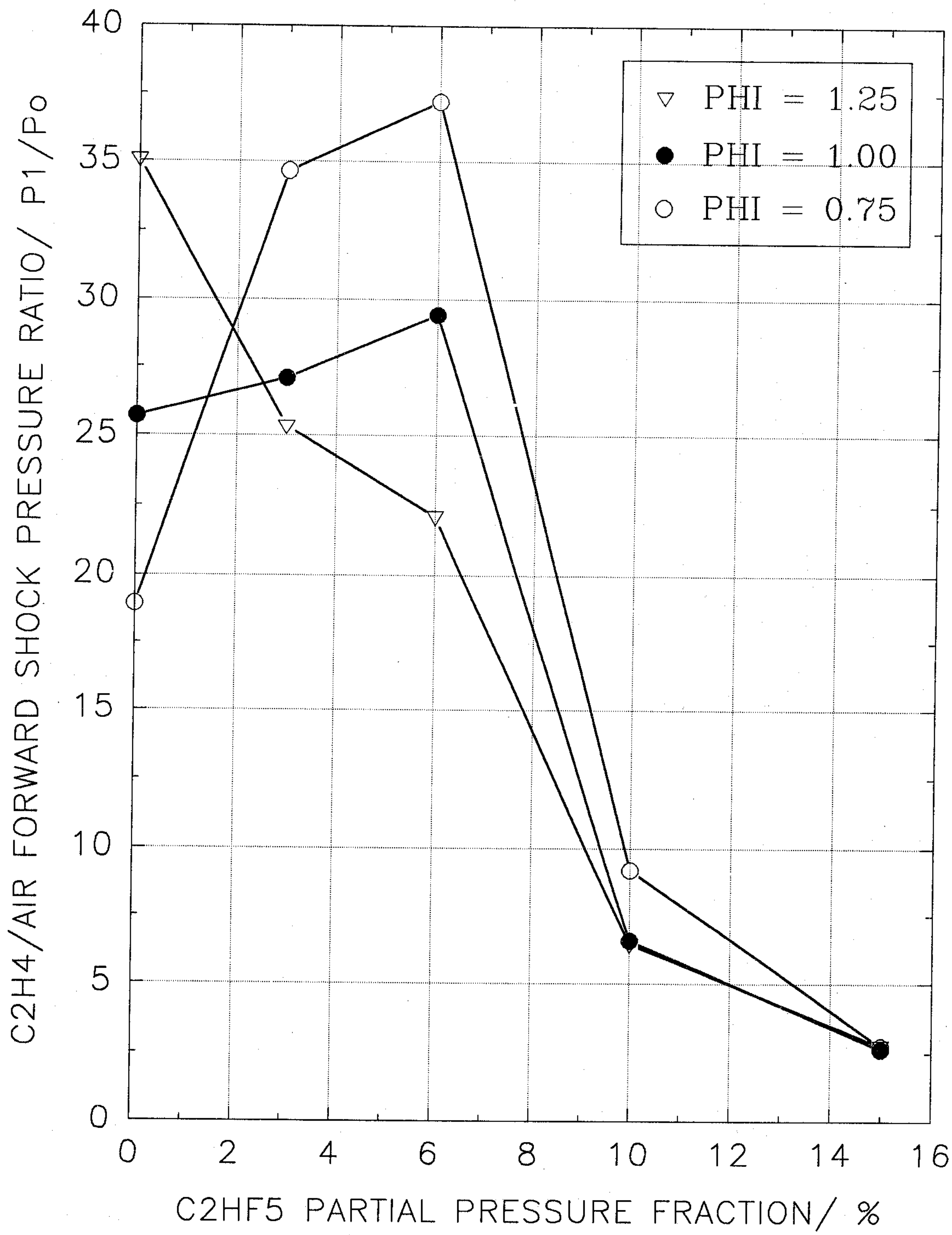


Figure 17. Shock pressure ratios in C_2HF_5/ethene/air mixtures (2.5 m, with spiral).

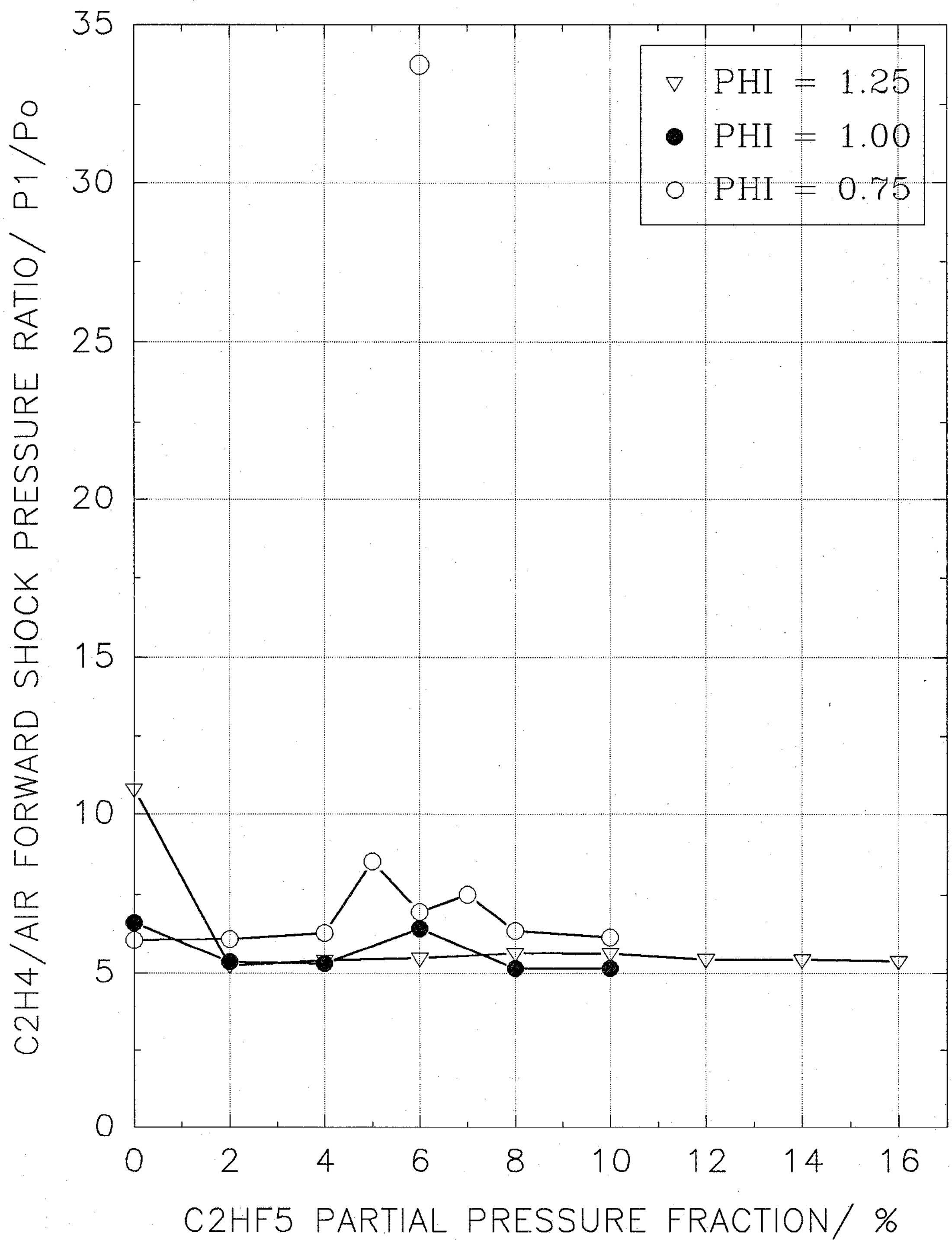


Figure 18. Shock pressure ratios in C_2HF_5/ethene/air mixtures (5.0 m, no spiral).

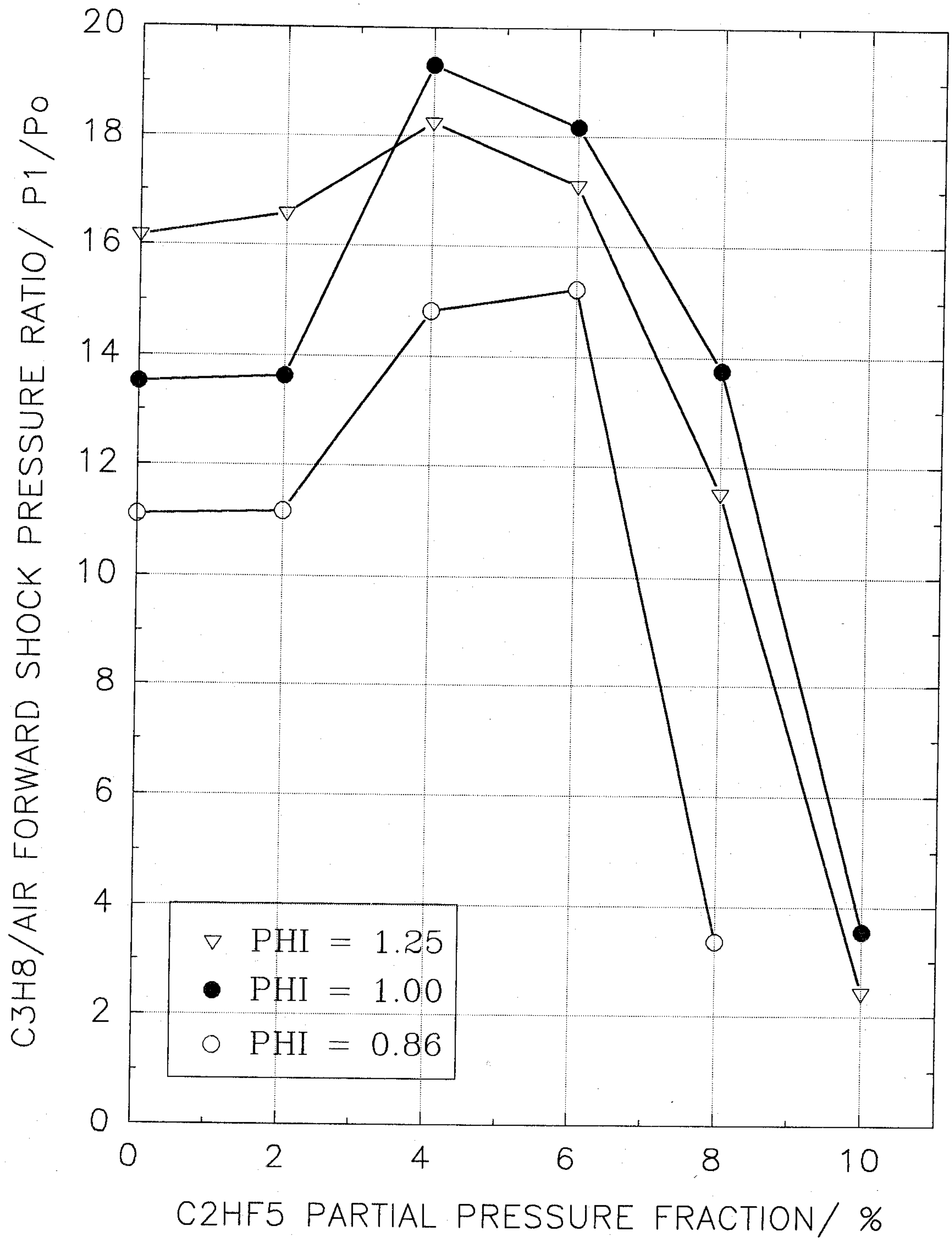


Figure 19. Shock pressure ratios in C_2HF_5/ethene/air mixtures (2.5 m, spiral).

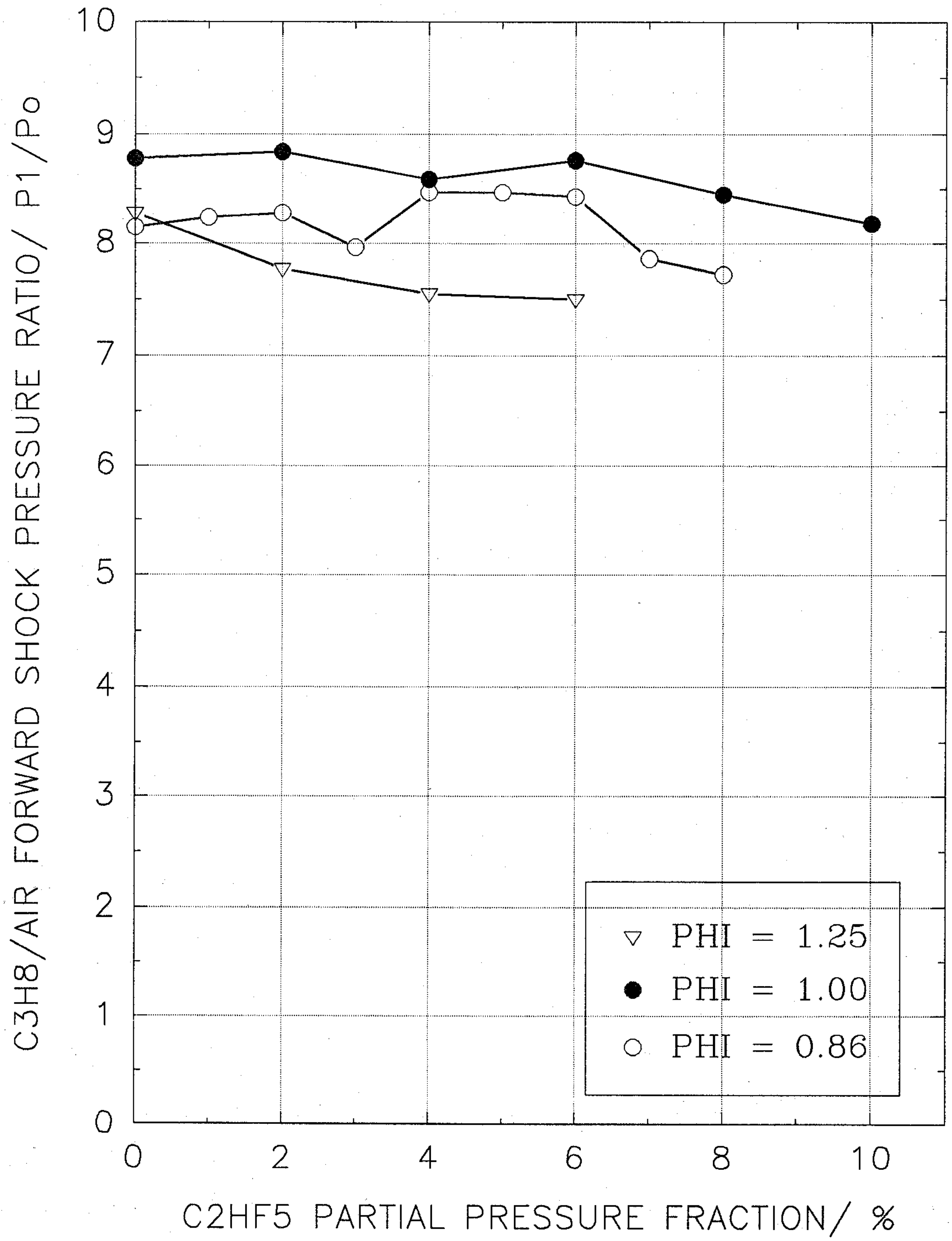


Figure 20. Shock pressure ratios in C_2HF_5/propane/air mixtures (5 m, no spiral).

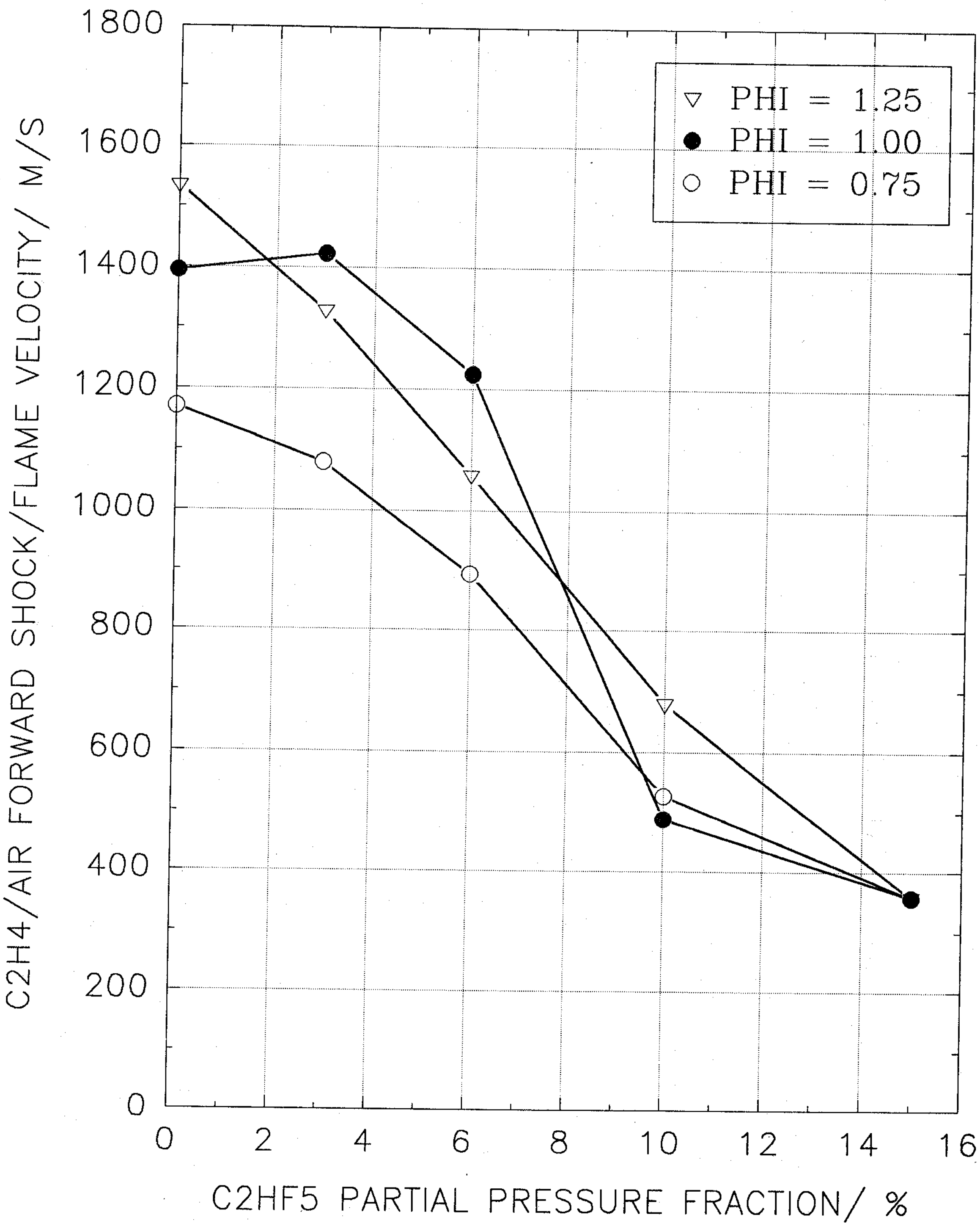


Figure 21. Shock/combustion wave speed in C_2HF_5/C_2H_4/air mixtures (2.5 m, spiral).

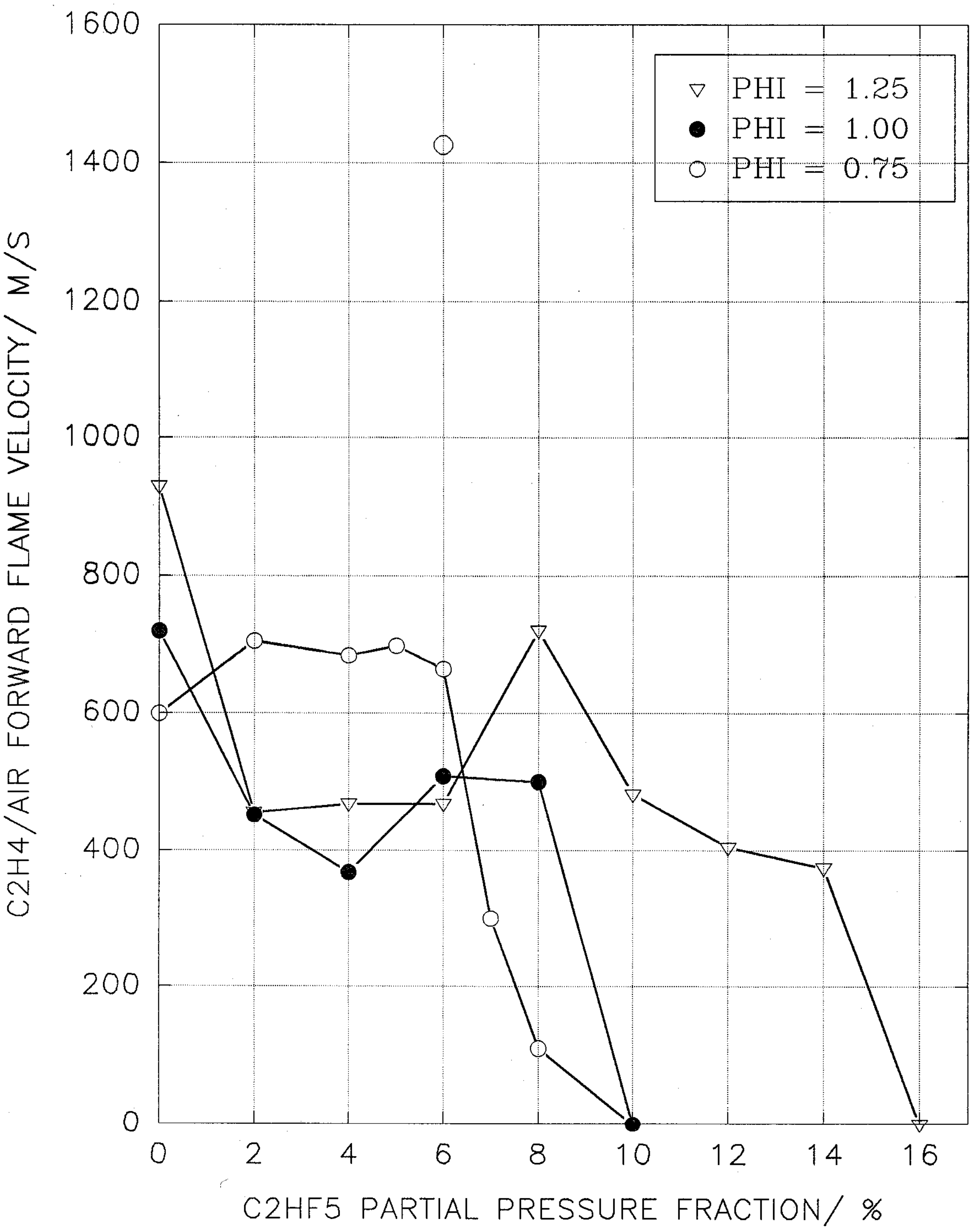


Figure 22. Combustion wave speed in C_2HF_5/C_2H_4/air mixtures (5 m, no spiral).

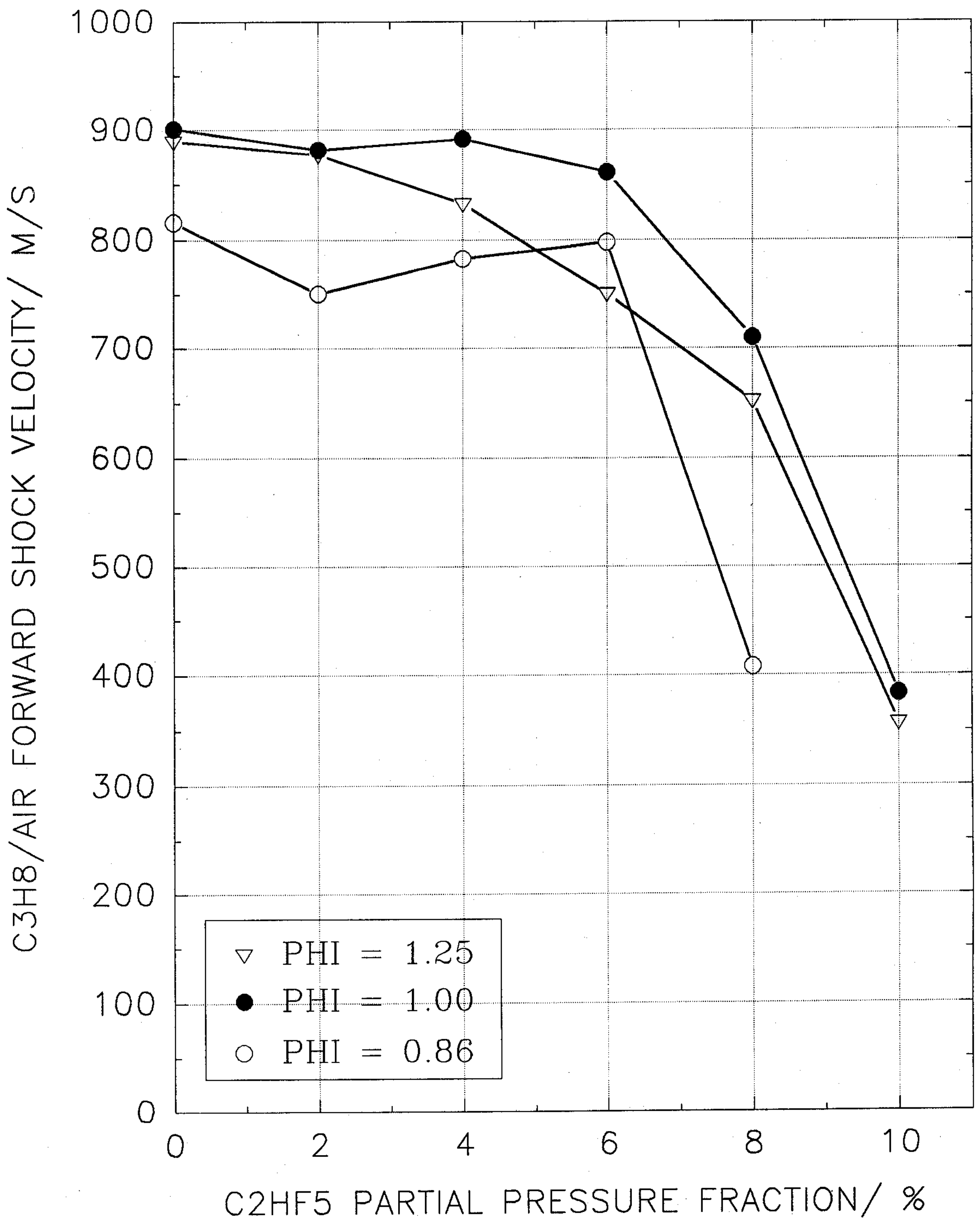


Figure 23. Shock/combustion wave speed in C_2HF_5/C_3H_8/air mixtures (2.5 m, spiral).

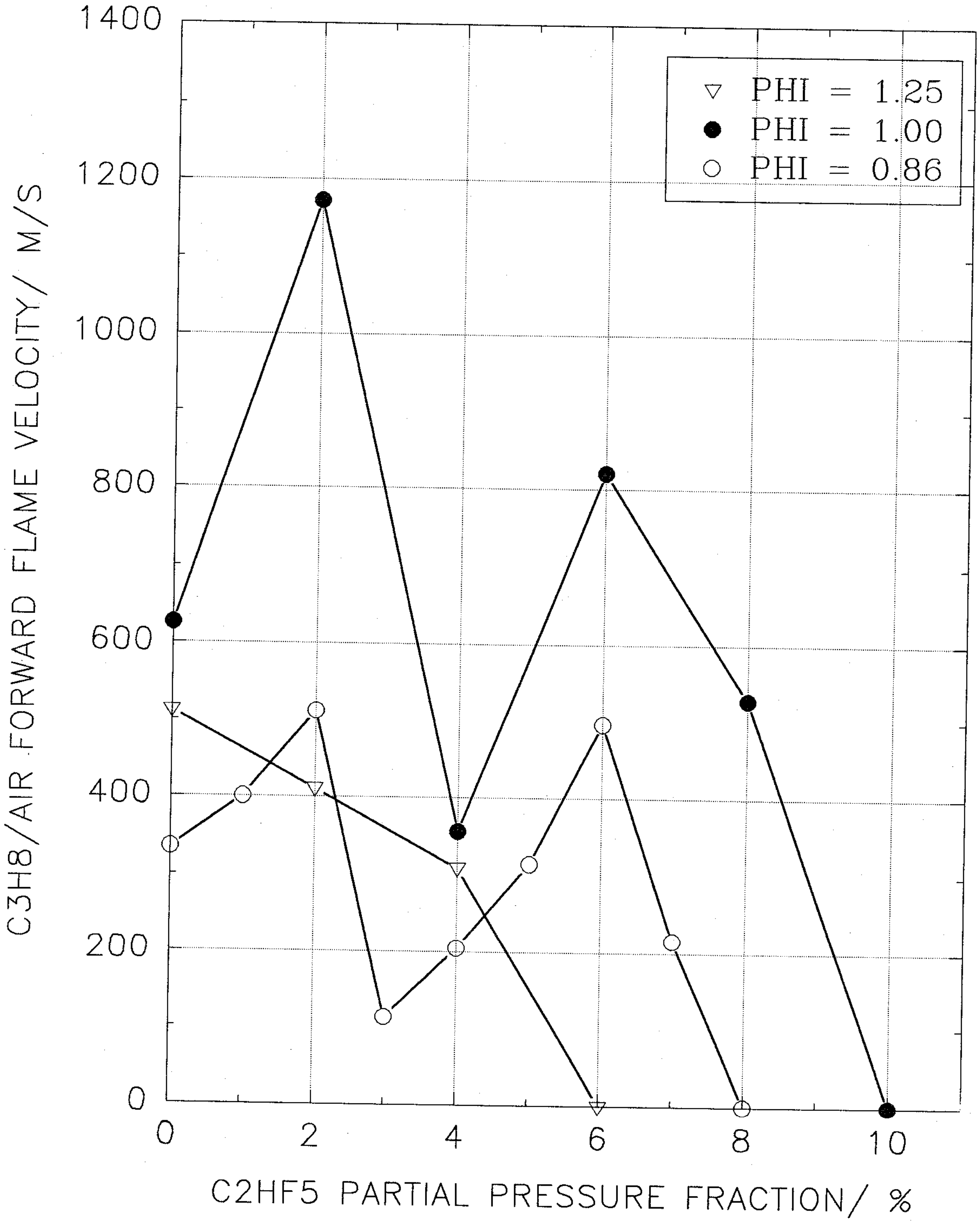


Figure 24. Combustion wave speed in C_2HF_5/C_3H_8/air mixtures (5 m, no spiral).

and Φ=1.25, the pressure rise in the uninhibited (partial pressure fraction = 0) test section increases substantially. However, the suppressant does not significantly worsen the situation for the stoichiometric mixture, and it is much more effective for the rich condition.

When the shorter, obstructed test section is replaced with the 5.0 m long unobstructed test section, the strength of the shock wave is decreased by a factor of about 3, as can be seen in Figure 18. For the rich and stoichiometric mixtures, adding as little as 2 % C_2HF_5 reduces the severity of the pressure build up. Additional agent has little impact on the pressure ratio. The behavior of the agent under lean conditions is less deleterious in the test section without the spiral in place. However, a small enhancement in pressure can be seen at a partial pressure fraction of 5 %. A single test at 6 % exhibited extreme pressures, although that data point could not be repeated.

Replacing ethene with propane cuts in half the pressures generated by the shock passing through the 2.5 m test section with the spiral insert. Figure 19 is a plot of P_1/P_0 as a function of the amount of HFC-125 added and the fuel/air equivalence ratio. The stoichiometric condition is the most dangerous with propane (compare to Figure 17), but for all equivalence ratios, the propane shock wave is easier to attenuate than the ethene-generated shock. In the long test section without the spiral insert, neither stoichiometry nor the amount of C_2HF_5 have much effect on the shock pressure ratio (see Figure 20).

The ethene/air mixture produces a quasi-detonation when the spiral is present in the 2.5 m test section. Thus, the shock and combustion wave travel together at the same speed. Figure 19 shows the wave speeds measured for this geometry as a function of stoichiometry and the amount of HFC-125 in the test section. Notice that the wave speed for the lean mixture decreases about monotonically with C_2HF_5 partial pressure, which is in contrast to the more complex behavior exhibited by the pressure ratio shown in Figure 17. When there is no spiral insert in the test section, the flame becomes decoupled from the shock. The flame velocities for different C_2HF_5/C_2H_4/air mixtures are plotted in Figure 22. The flame speed is much slower than the shock speed and goes to zero when the HFC-125 reaches a partial pressure fraction of 10 % for Φ = 0.75 and 1.0. A 16 % partial pressure fraction is required when the fuel/air ratio is rich. The outlying point for the lean mixture with 6 % agent has the correspondingly high pressure ratio shown in Figure 18. The rather chaotic looking behavior in Figure 22 can be partially attributed to the location of the photodiodes (0.3 m beyond the gate valve), where the gradient in agent concentration is high and the wake created by the gate valve may be influencing the flow field.

The shock and combustion wave travel together when propane is the fuel and the spiral insert is in the 2.5 m test section. The behavior of the wave speed (see Figure 23) is qualitatively similar to the ethene system, although the maximum speeds are lower and the amount of C_2HF_5 required to quench the combustion (*i.e.*, speed < 400 m/s) is a couple of percent lower with propane. Figure 24 shows the combustion wave speed without a spiral insert. The stoichiometric mixture produces the fastest flame, and is quenched when the C_2HF_5 partial pressure fraction is 10 %. Comparing this plot to Figure 22, it is interesting to note that the rich propane flame can be fully suppressed at a concentration less than half the value required to suppress rich ethene combustion.

2.4.4.2 C_3F_8 Performance. The perfluoropropane (FC-218) does not produce the high overpressures found when C_2HF_5 is added to the lean ethene mixture in the presence of the spiral insert. Figure 25 shows the shock pressure ratio measured in the obstructed configuration with the C_3F_8/C_2H_4/air mixture. There is a slight enhancement when the partial pressure fraction is 2 %, but otherwise the drop-off in P_1/P_0 with agent concentration is well-behaved. The lean mixture is the easiest and the rich mixture the most difficult to suppress with C_3F_8, which is opposite to the results observed when C_2HF_5 was the agent.

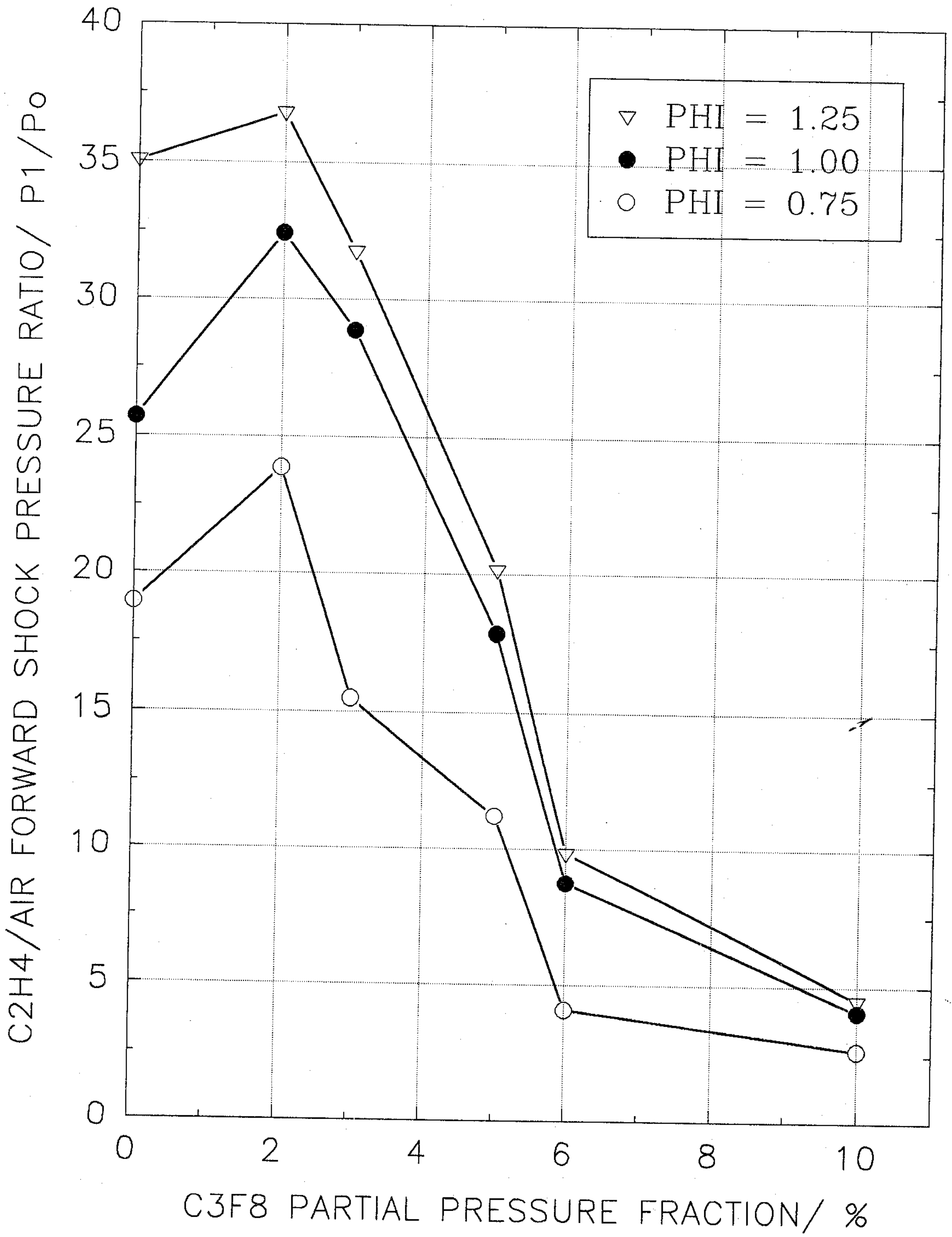


Figure 25. Shock pressure ratio in C_3F_8/C_2H_4/air mixtures (2.5 m, no spiral).

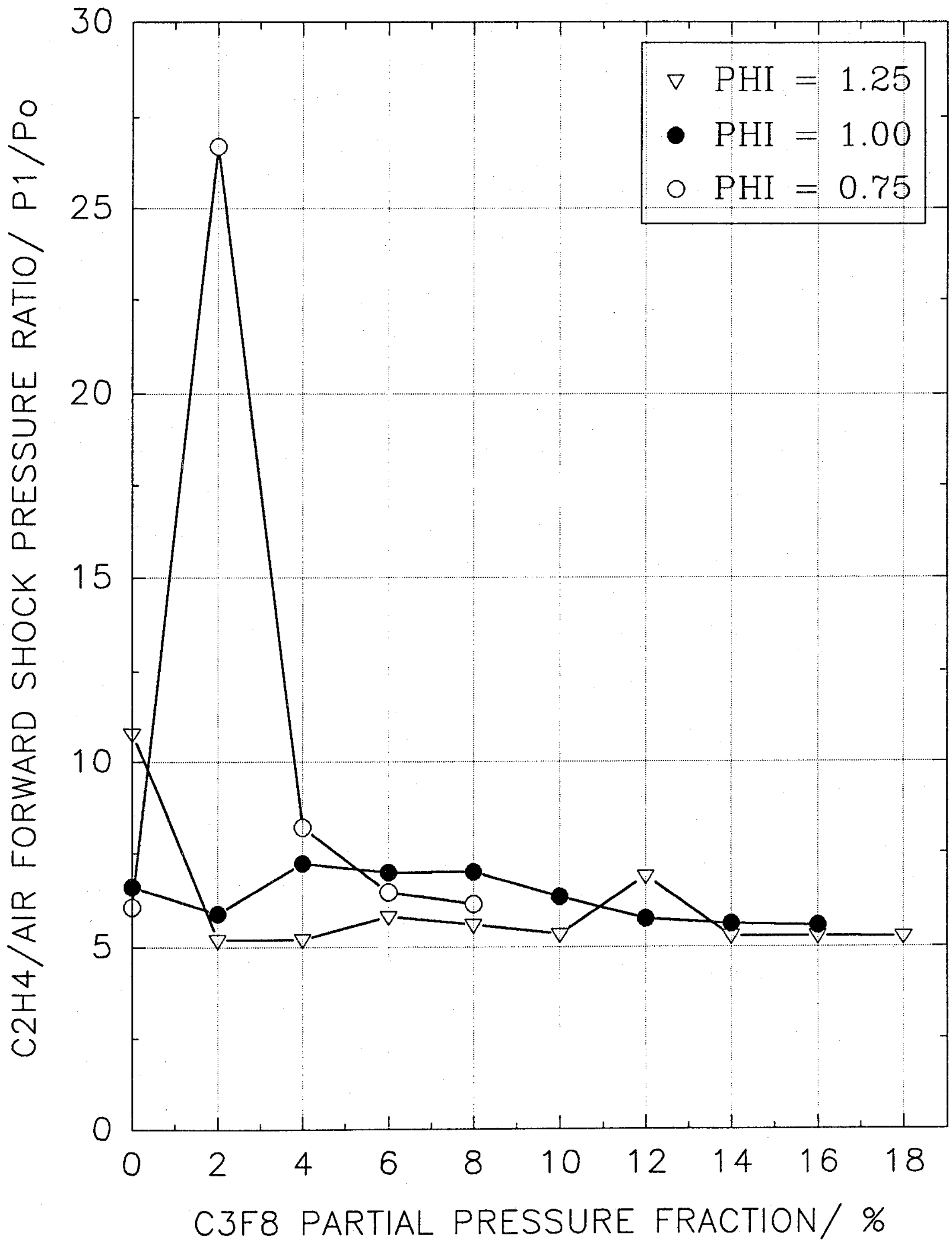


Figure 26. Shock pressure ratio in C_3F_8/C_2H_4/air mixtures (5 m, no spiral).

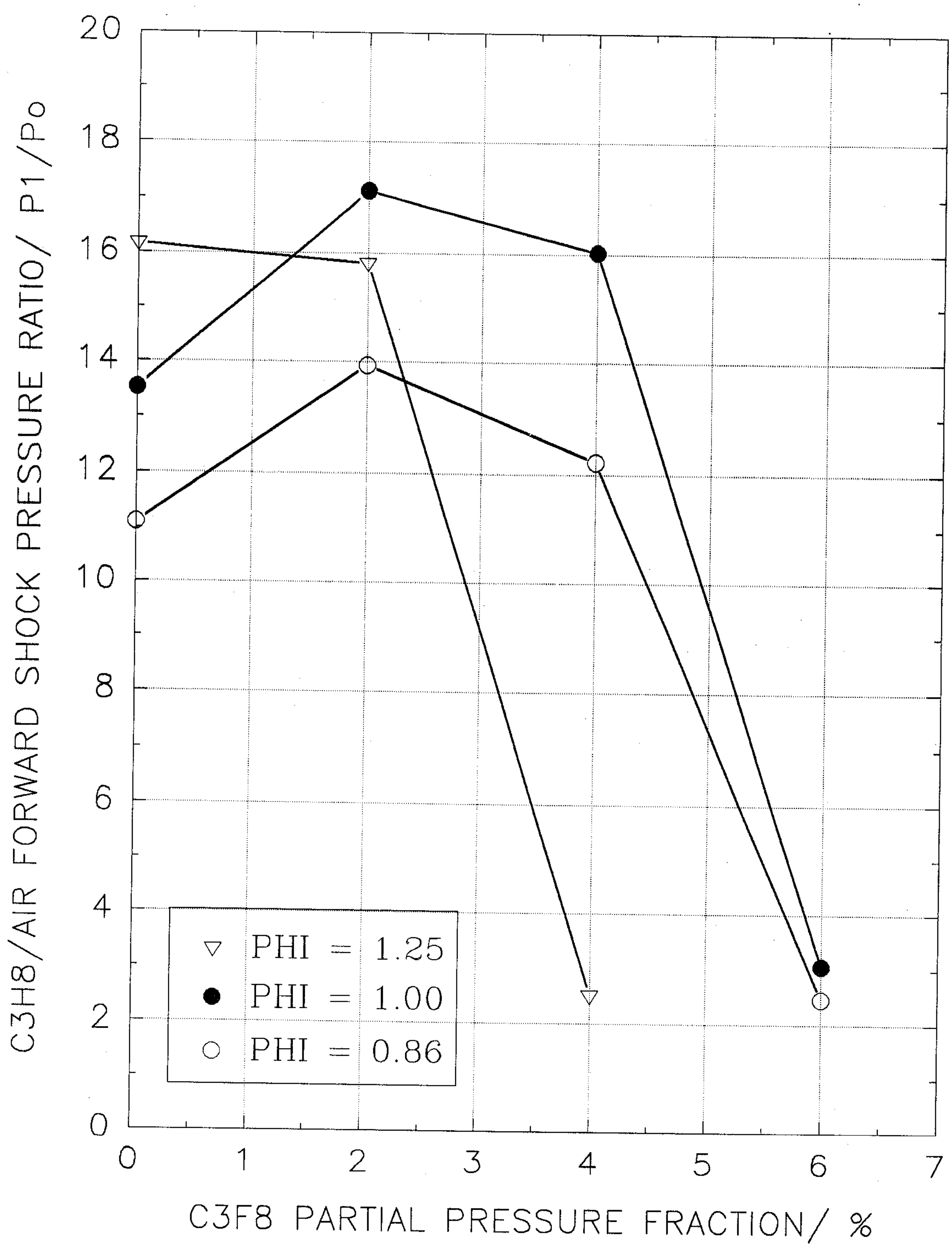


Figure 27. Shock pressure ratio in C_3F_8/C_3H_8/air mixtures (2.5 m, spiral).

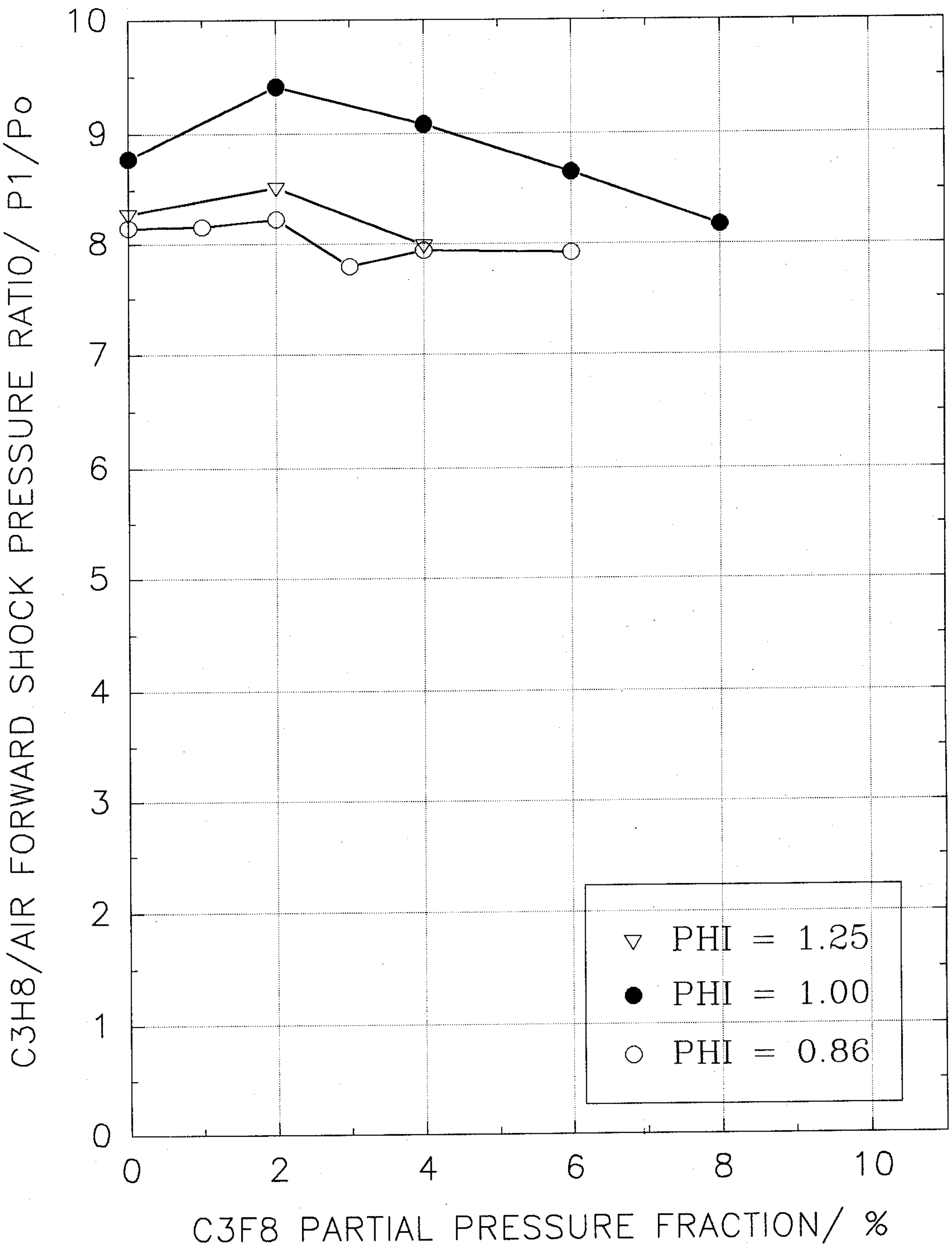


Figure 28. Shock pressure ratio in C_3F_8/C_3H_8/air mixtures (5 m, no spiral).

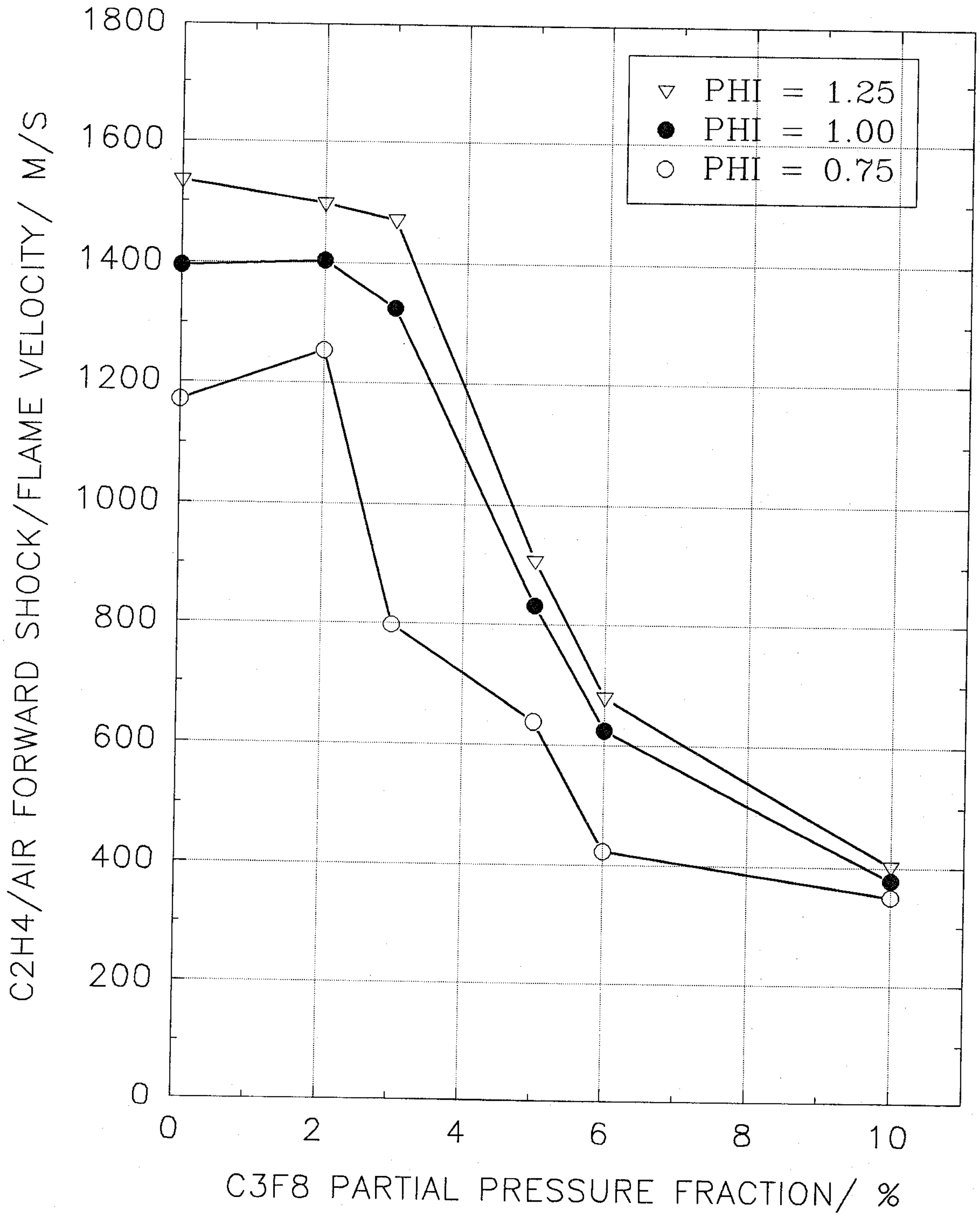


Figure 29. Shock/combustion wave speed in C_3F_8/C_2H_4/air mixtures (2.5 m, spiral).

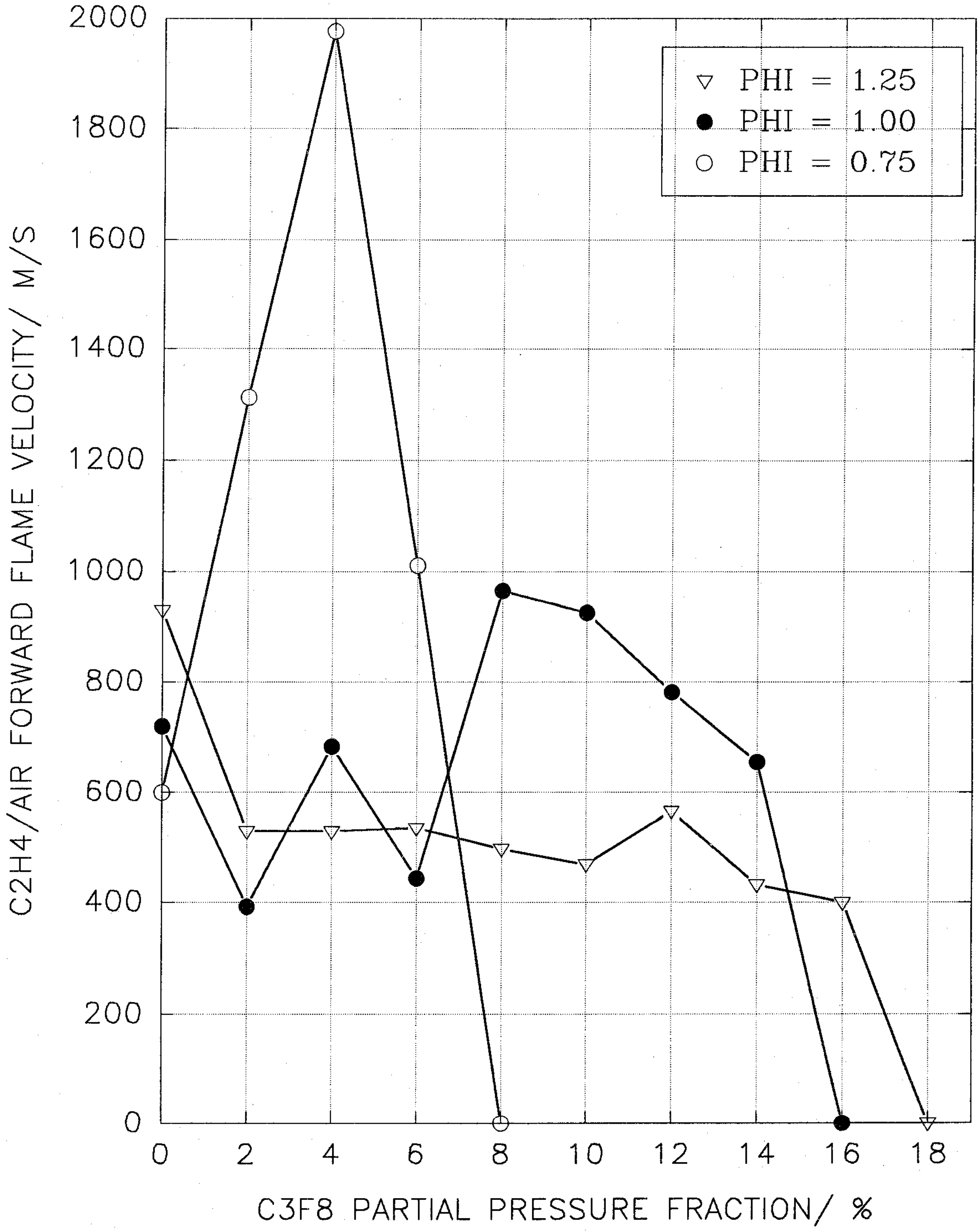


Figure 30. Combustion wave speed in C_3F_8/C_2H_4/air mixtures (5 m, no spiral).

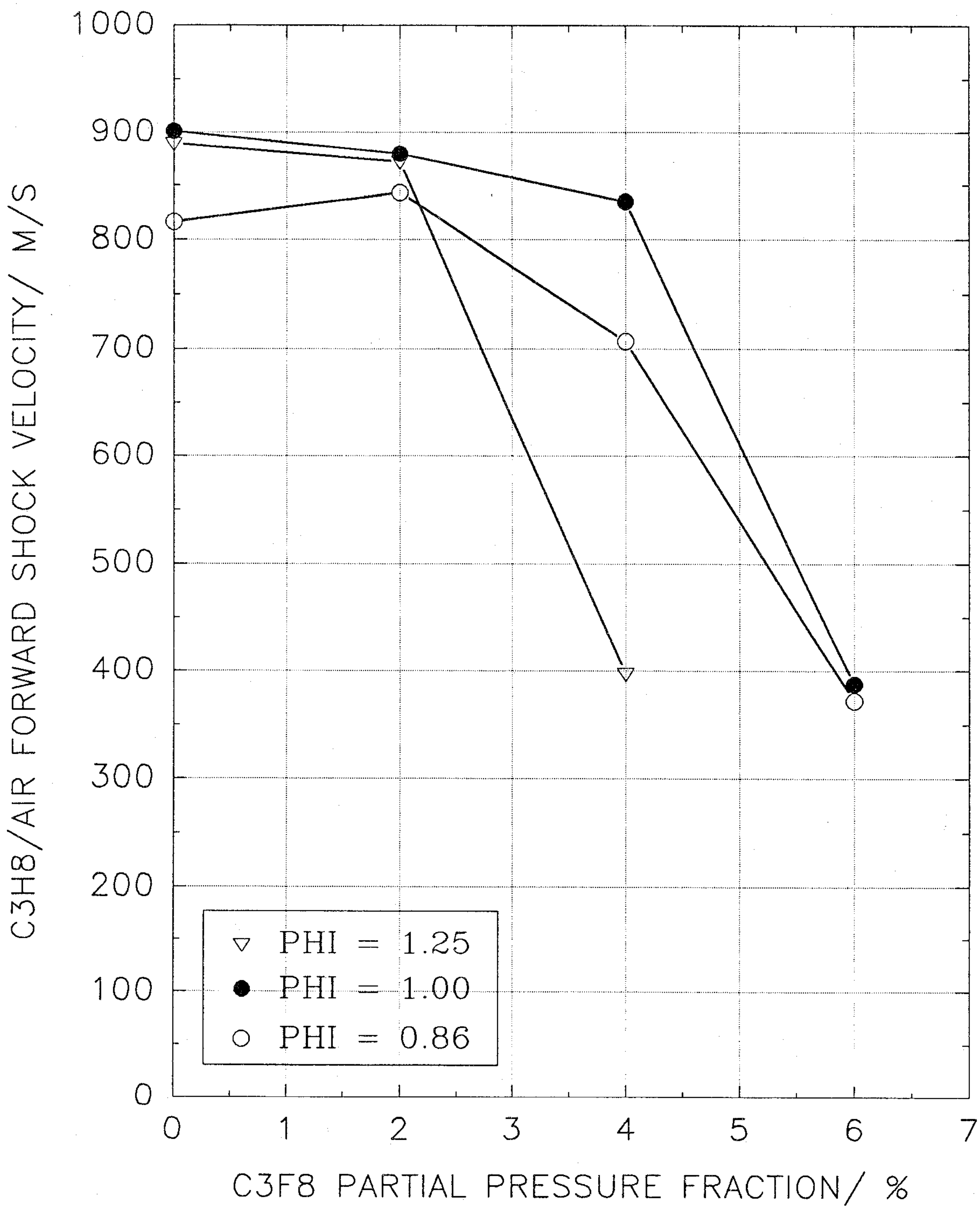


Figure 31. Shock/combustion wave speed in C_3F_8/C_3H_8/air mixtures (2.5 m, spiral).

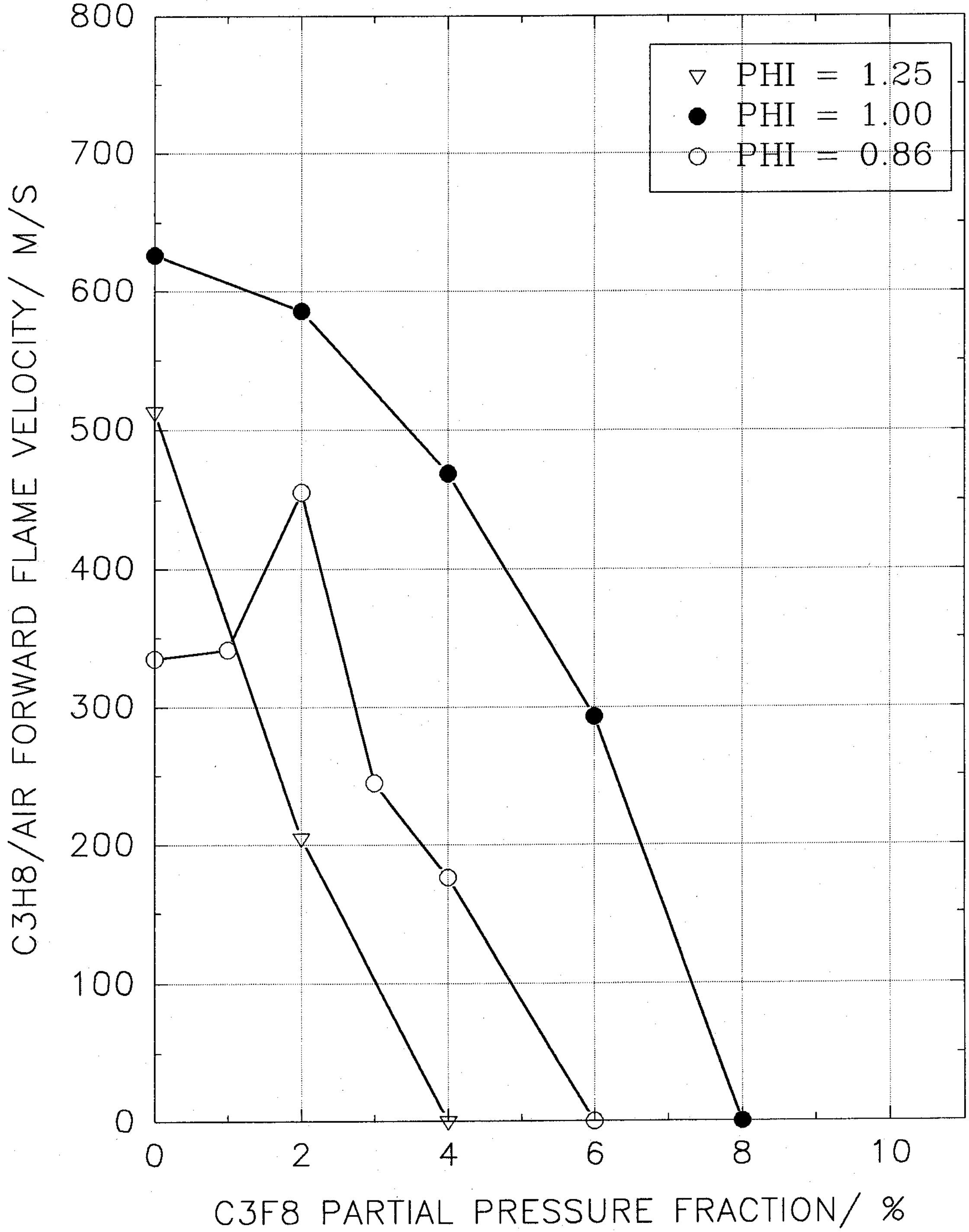


Figure 32. Combustion wave speed in C_3F_8/C_3H_8/air mixtures (5 m, no spiral).

By removing the spiral, the pressure rise across the shock is greatly reduced, and the suppression behavior of C_3F_8 is very similar to C_2HF_5, as can be seen by comparing Figure 26 to Figure 18. The pressure spike in the lean mixture containing C_3F_8 cannot be easily explained, but may have something to do with the sensitivity of the ethene/air reaction to small perturbations. Note that a spike is also present in Figure 18, but that is hypothesized to be related to the hydrogen in the HFC-125 and its impact on the chain branching reactions.

The FC-218 does a much better job than HFC-125 in reducing the pressure buildup in the obstructed propane/air experiments. Figure 27 shows that a 4 % partial pressure fraction of C_3F_8 attenuates the shock wave traveling through the rich mixture as effectively as 2.5 times as much C_2HF_5. Suppression of the lean propane mixture requires 6 % C_3F_8, compared to 8 % C_2HF_5. Figure 28 compares the shock pressure ratios for the lean, stoichiometric and rich propane/air mixtures in the 5 m long test section without the spiral insert. The FC-218 has little impact on the strength of the shock wave under these conditions. The same statement applies to HFC-125 (see Figure 20).

The combined shock and combustion wave speeds are plotted in Figure 29 for the C_3F_8-suppressed C_2H_4/air mixture in the obstructed 2.5 m long test section. The speed decreases with the addition of FC-218 more quickly, dropping below 400 m/s at a partial pressure fraction of 10 % (compared to 15 % when HFC-125 is the agent). Removing the insert results in the combustion wave speeds shown in Figure 30. The very high speed for the lean mixture with 4 % C_3F_8 corresponds to a Chapman-Jouguet detonation, a result that is difficult to have predicted, especially since full suppression is attained when only 8 % C_3F_8 is added to the mixture. The rich flame travels more slowly at low agent concentrations, but is not fully extinguished until the partial pressure fraction is 18 %. The speed of the propane combustion waves are plotted in Figures 31 and 32, with and without the spiral insert, respectively. The FC-218 out-performs the HFC-125 under both arrangements (compare to Figures 23 and 24). Under the worst conditions, only 8 % C_3F_8 is necessary to annihilate the propane flame.

2.4.4.3 CF_3I Performance. The suppression behavior of CF_3I is more complicated than either C_2HF_5 or C_3F_8. This complexity is demonstrated in Figure 33, which shows that small concentrations of CF_3I dramatically reduce the shock pressure ratio generated in the obstructed 2.5 m long test section filled with C_2H_4/air mixtures. However, the pressures rise as the agent partial pressure fraction is increased to 6 %, equalling or exceeding the totally uninhibited values. For the most reactive mixture ($\Phi = 1.25$), it takes over 13 % CF_3I to reduce the pressure ratio to below 5.1, as compared to about 12 % for C_2HF_5 and less than 10 % for C_3F_8. The unpredictable behavior extends to the test configuration with no spiral insert (see Figure 34). In these tests, it is the richest condition that is the best behaved. For an equivalence ratio of 0.75, the pressure increases to a factor greater than 36:1 when the partial pressure fraction of CF_3I is 4 %. This peak shifts to 8 % when the C_2H_4/air mixture is stoichiometric. Similar peaks were observed when HFC-125 and FC-218 were used (compare to Figures 18 and 26), but only for $\Phi = 0.75$. The precision of the CF_3I suppression measurements were checked by repeating four times the 8 % CF_3I in stoichiometric ethene/air mixture. The maximum absolute deviations of flame and shock velocities and pressure ratio were 157 m/s, 15 m/s and 0.97 respectively. This level of precision provides confidence that the trends observed in all the experimental sequences are real and meaningful.

The shock pressure ratio generated in obstructed lean, stoichiometric and rich CF_3I/C_3H_8/air mixtures is shown in Figure 35. The behavior is similar to that observed with C_2H_4, except that the stoichiometric mixture requires much more agent to get under control. With the spiral removed (Figure 36), the pressure ratio drops down more quickly when propane is the fuel, but the stoichiometric condition persists.

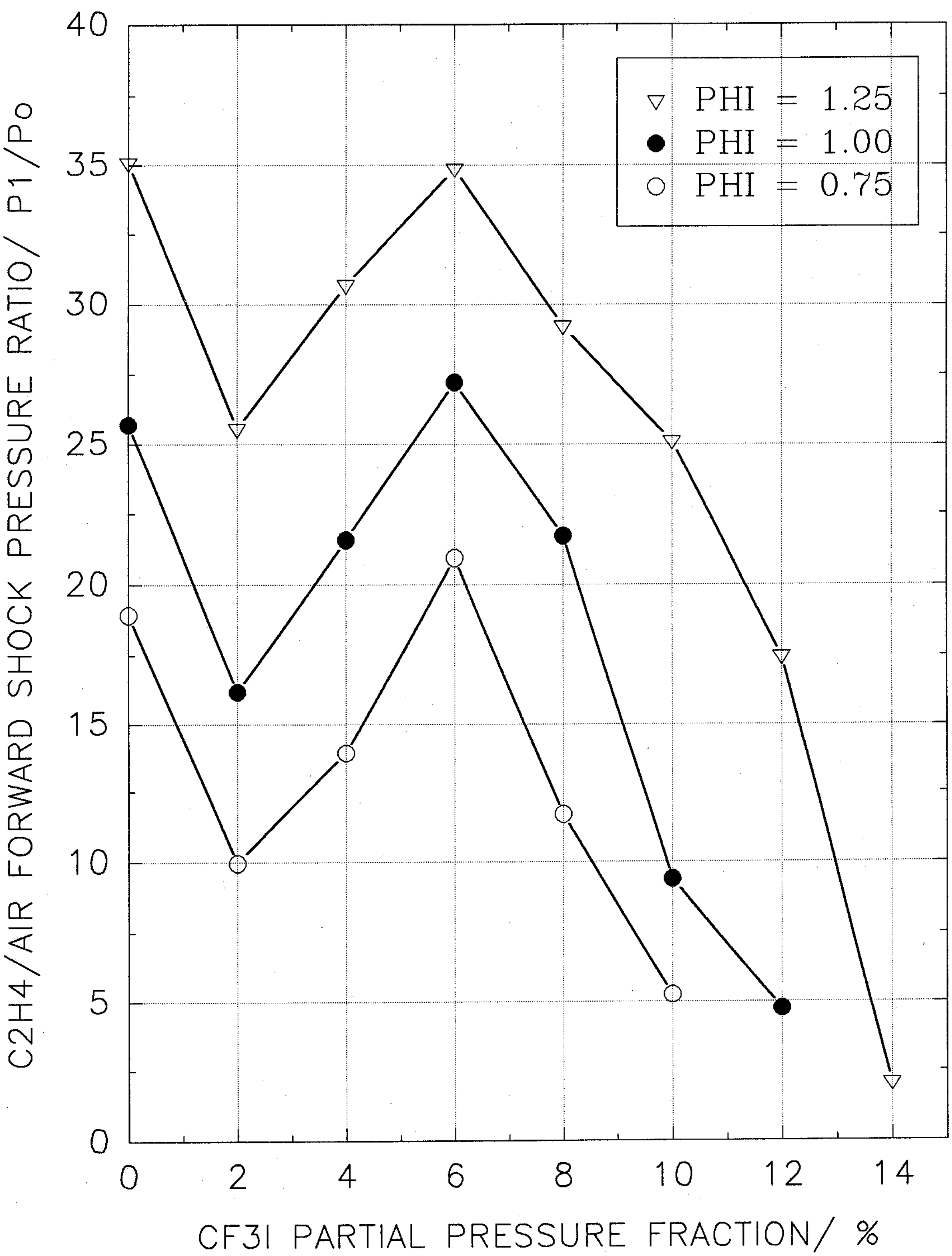


Figure 33. Shock pressure ratio in CF_3I/C_2H_4/air mixtures (2.5 m, no spiral).

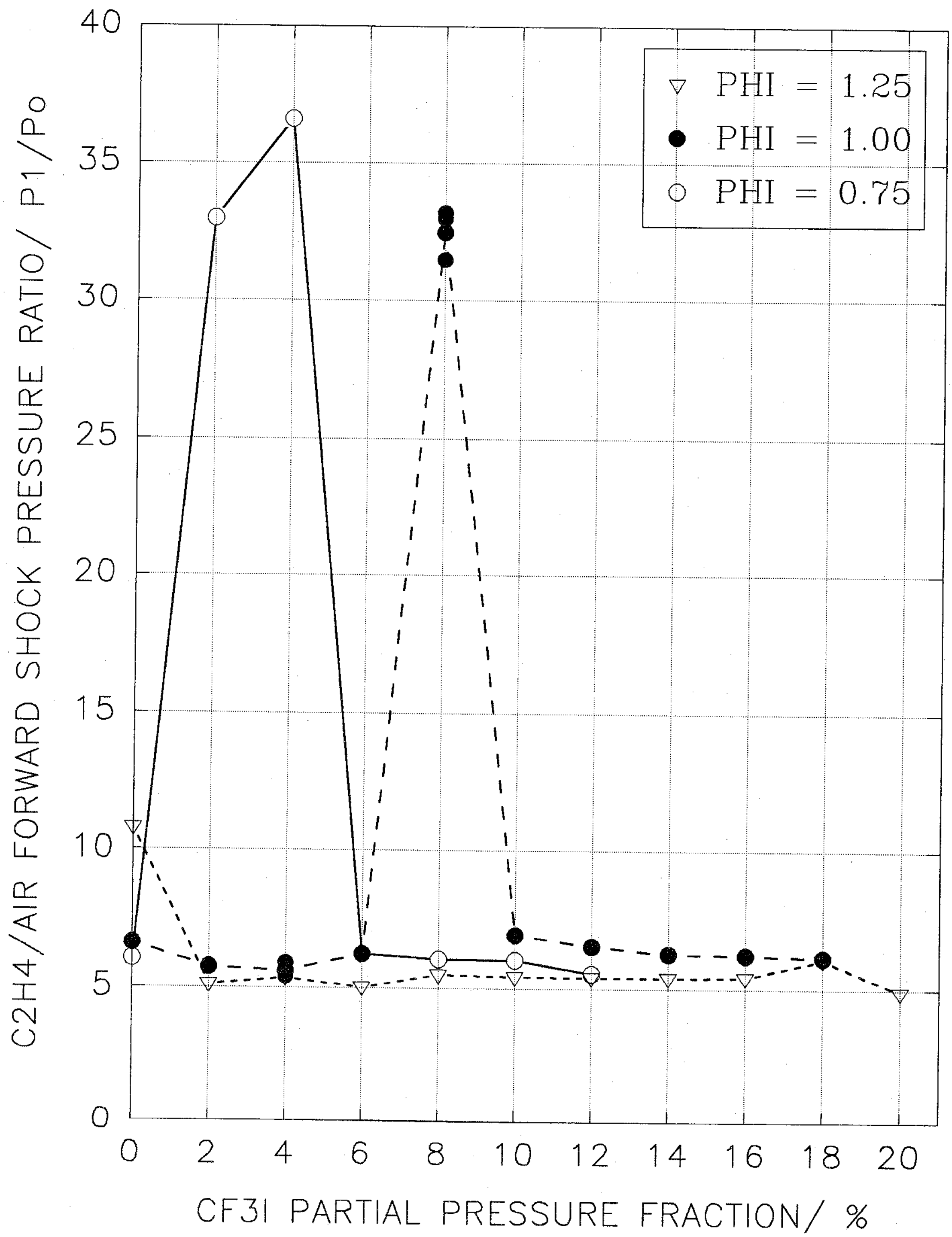


Figure 34. Shock pressure ratio in CF_3I/C_2H_4/air mixtures (5 m, no spiral).

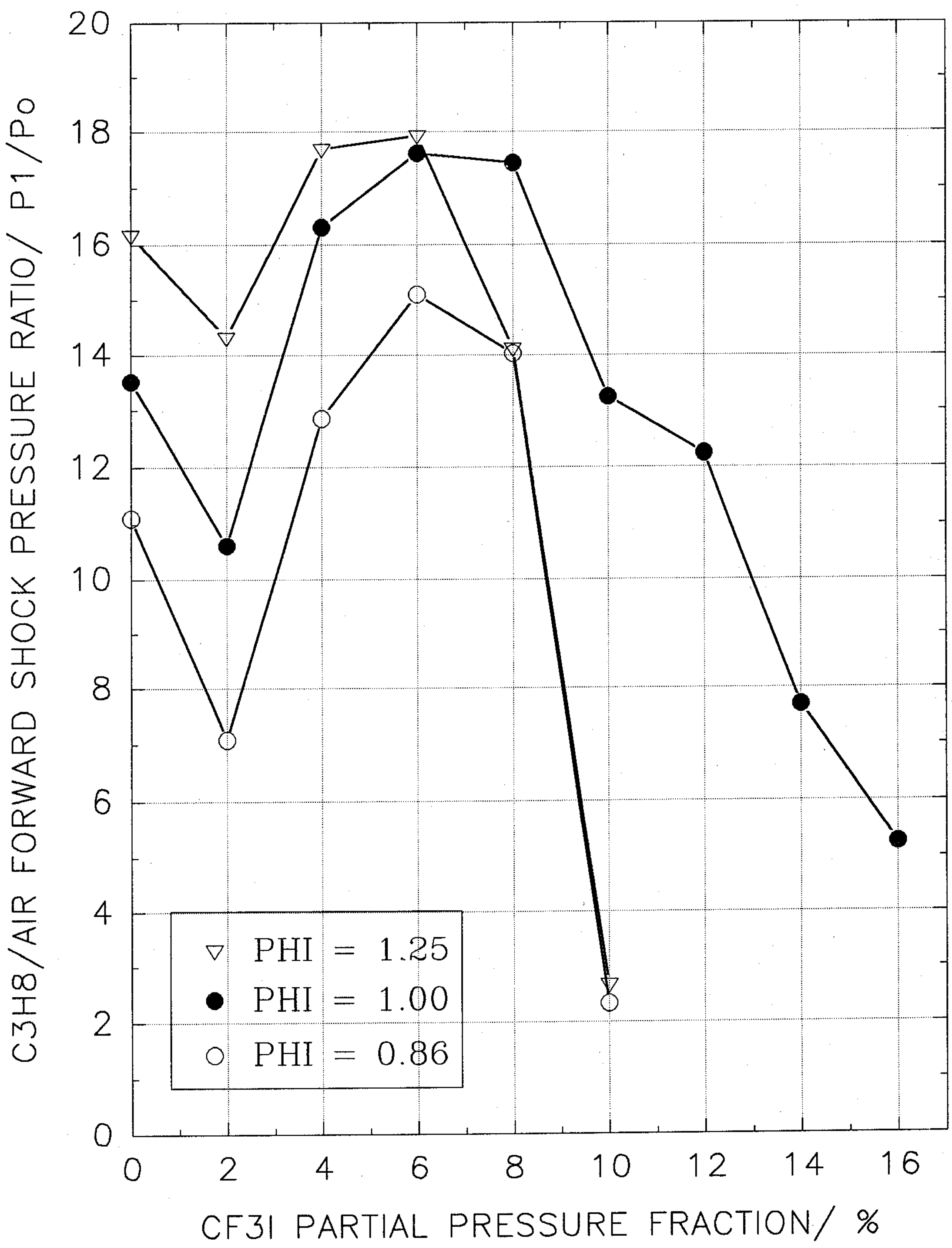


Figure 35. Shock pressure ratio in CF_3I/C_3H_8/air mixtures (2.5 m, spiral).

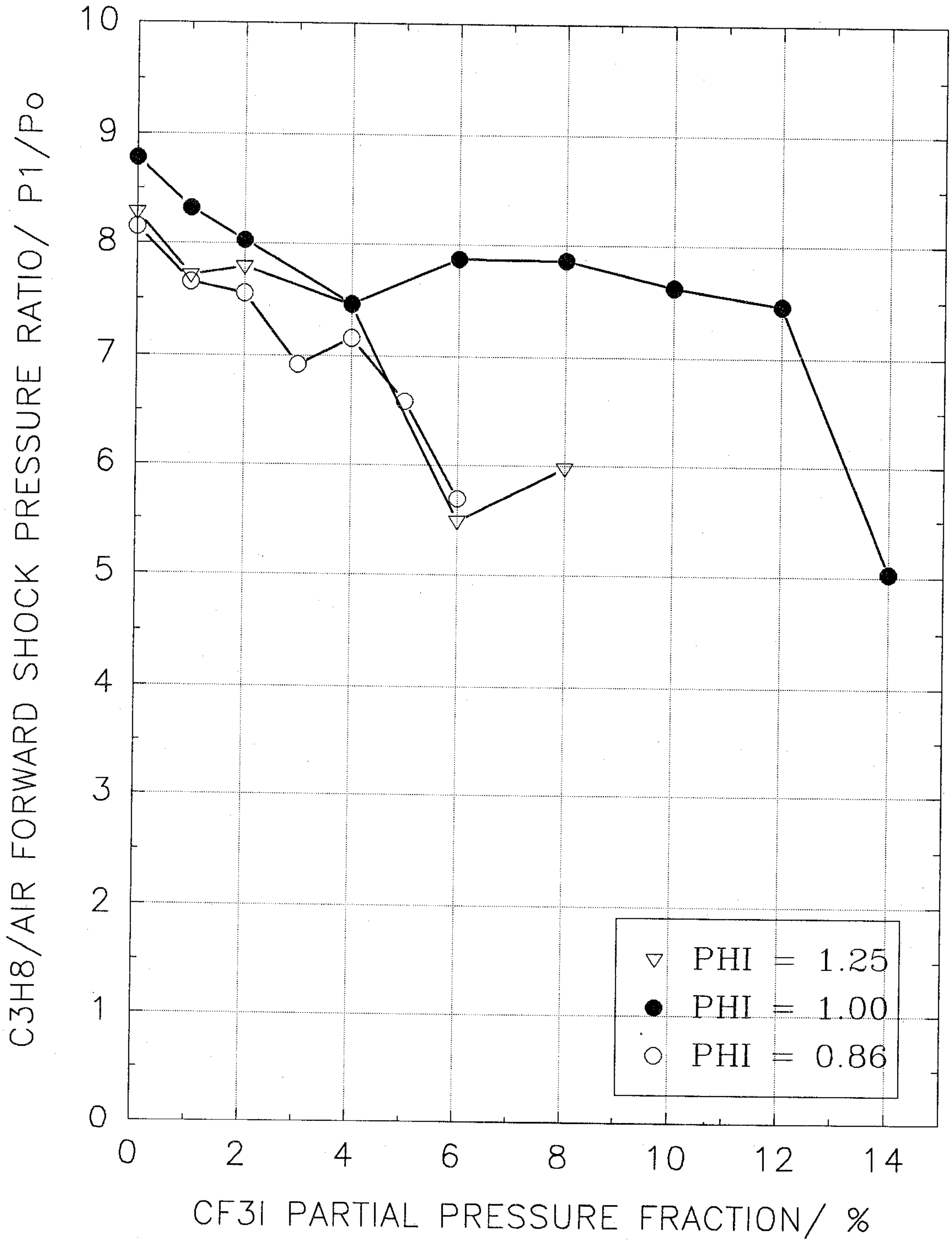


Figure 36. Shock pressure ratio in CF_3I/C_3H_8/air mixtures (5 m, no spiral).

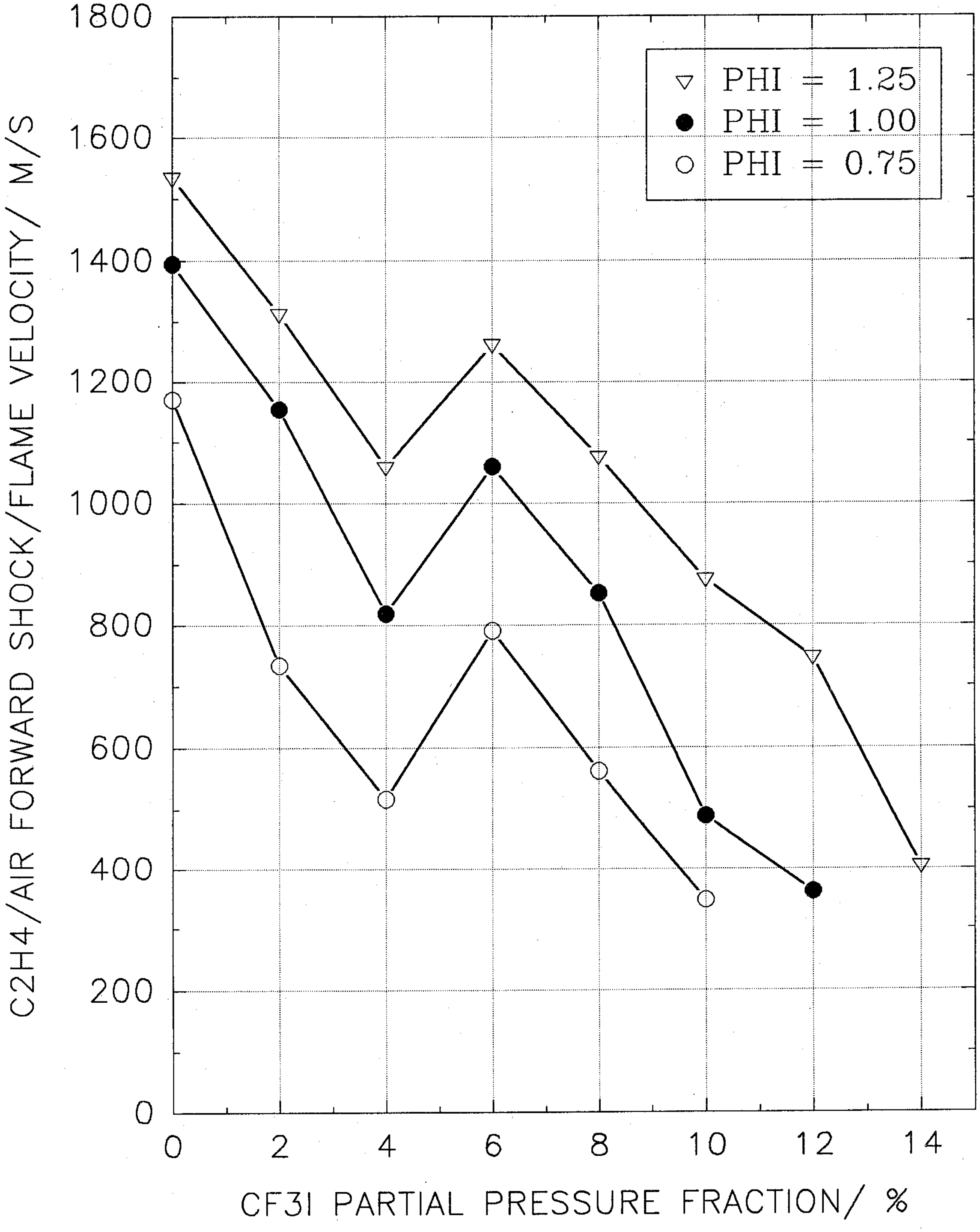


Figure 37. Shock/combustion wave speed in CF_3I/C_2H_4/air mixtures (2.5 m, spiral).

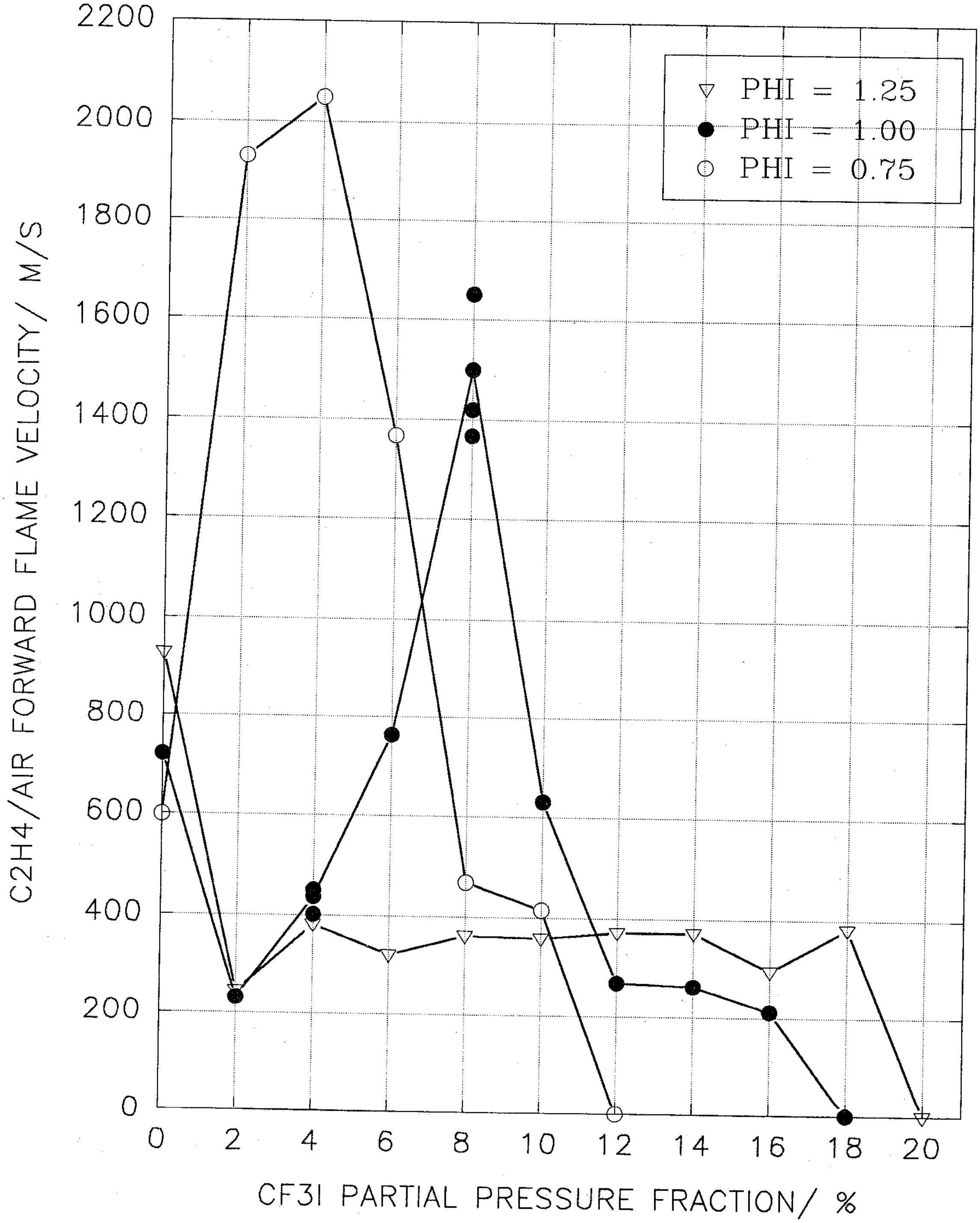


Figure 38. Combustion wave speed in CF_3I/C_2H_4/air mixtures (5 m, no spiral).

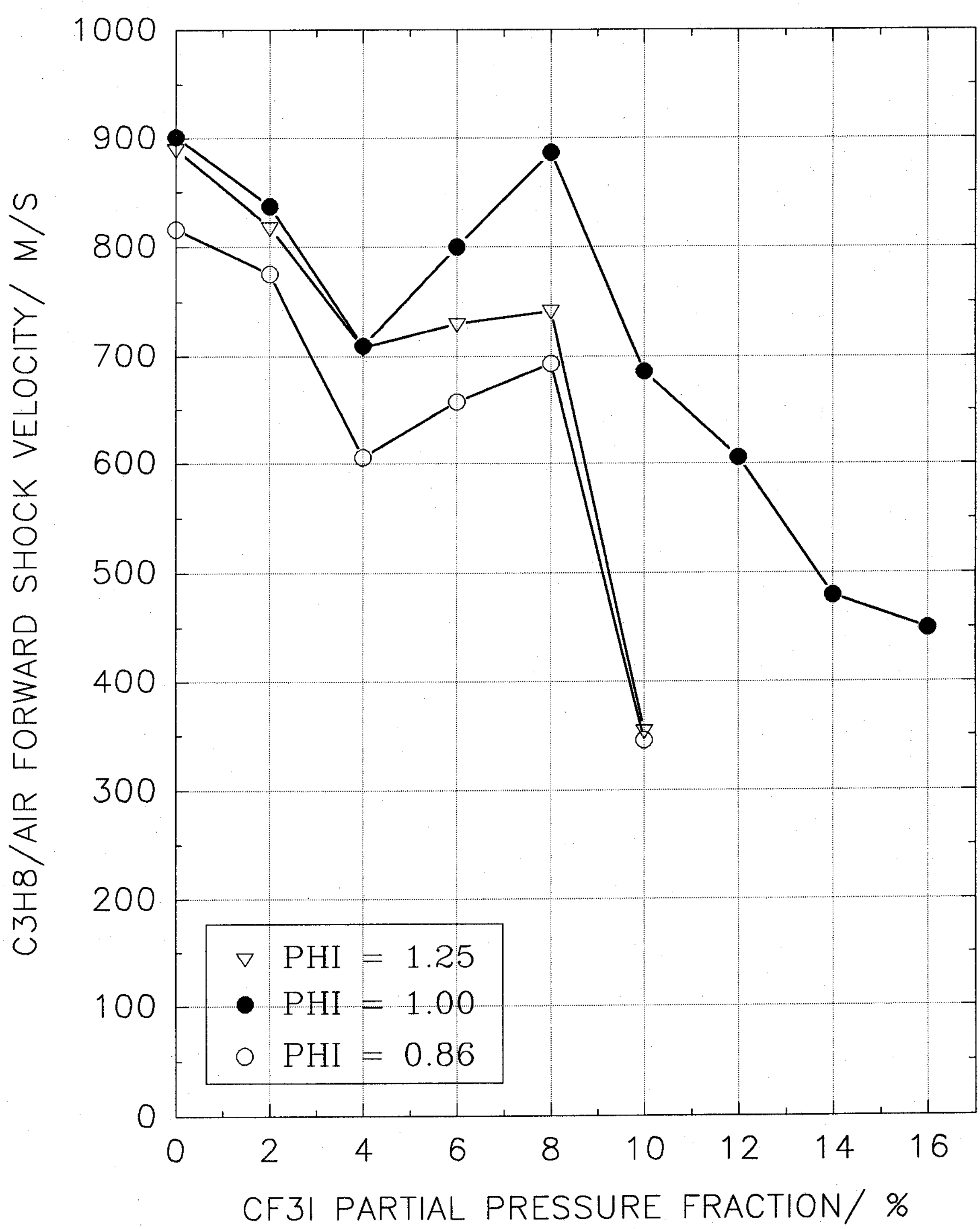


Figure 39. Shock/combustion wave speed in CF_3I/C_3H_8/air mixtures (2.5 m, spiral).

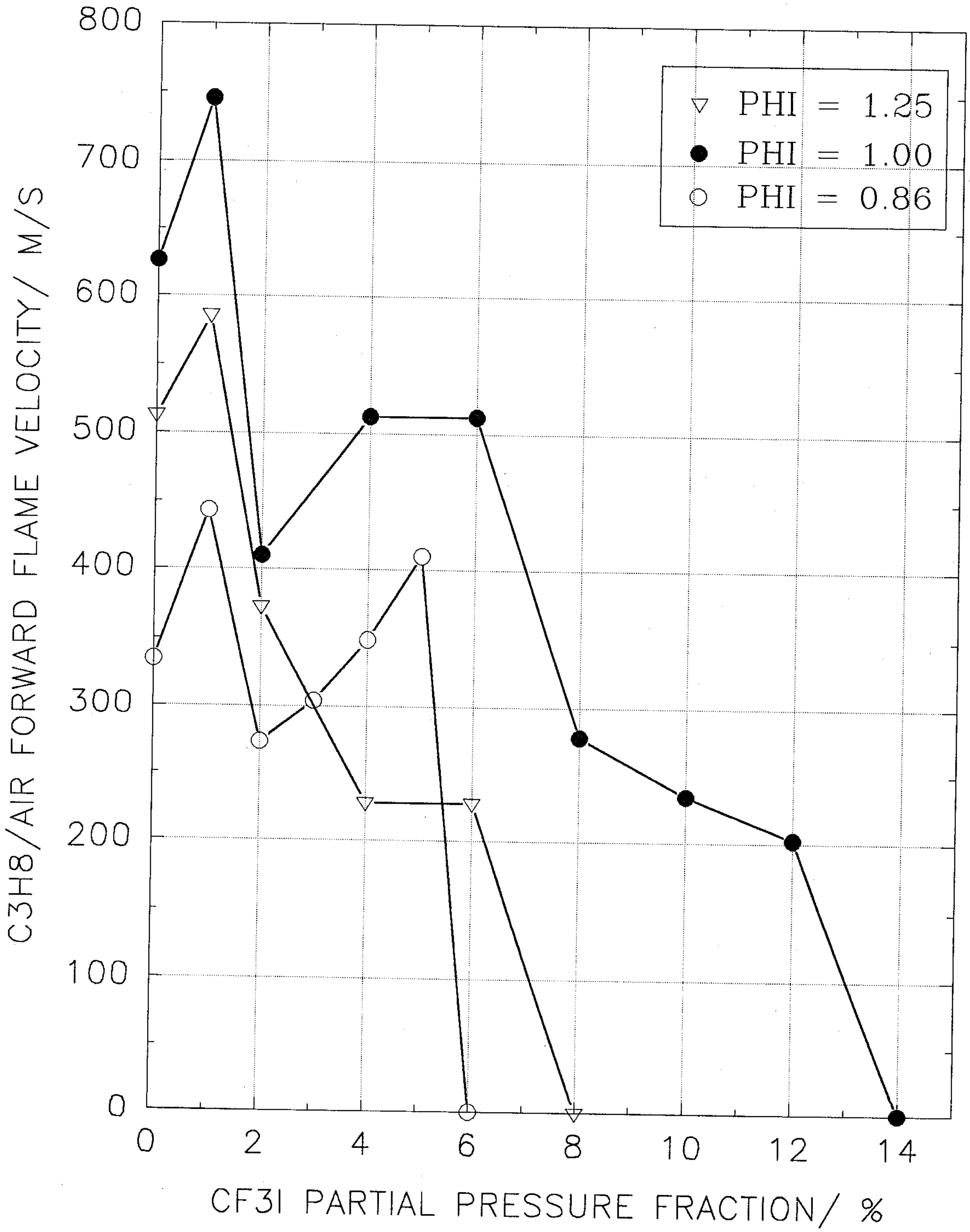


Figure 40. Combustion wave speed in CF_3I/C_3H_8/air mixtures (5 m, no spiral).

The wave speeds are congruent with the pressure ratio results. In Figure 37, the shock and combustion waves are merged. The local minimum in wave speed occurs at a partial pressure fraction of 4 %, which is slightly higher than the location of the minimum pressure ratio. The behavior of the combustion wave can be seen most clearly in Figure 38. Acceleration to a Chapman-Jouguet detonation is clearly observed for both the lean and stoichiometric C_2H_4/air mixtures. The rich mixture requires 20 % CF_3I to quench the flame radiation, compared to 16 % and 18 % for the HFC-125 and FC-218, respectively.

Figures 39 and 40 show the shock and combustion wave speeds when C_3H_8 is the fuel. The stoichiometric mixture requires the most CF_3I to decelerate, but much less agent is required as compared to C_2H_4 combustion. Similar to C_2HF_5 and C_3F_8, no C-J detonations are produced using CF_3I when propane is the fuel.

2.4.4.4 Relative Performance of C_2HF_5, C_3F_8, and CF_3I. Relative performance of the three compounds is compared as a function of the fuel and test section configuration in Figures 41 to 44. The stoichiometric mixture is chosen as representative. When ethene is the fuel and the spiral insert is in place, the uninhibited shock/combustion wave speed is 1400 m/s. Figure 41 shows that the CF_3I is the most efficient at reducing the wave speed for partial pressure fractions of 4 % and below. The FC-218 (C_3F_8) reduces the wave speed most effectively at higher concentrations, attaining a fully-suppressed condition of 400 m/s at less than 10 %. Removing the spiral reduces the initial condition to a high-speed deflagration traveling at 700 m/s (see Figure 42). The C_2HF_5 quenches the radiation completely with a partial pressure fraction of 10 %. The C_3F_8 is less efficient in suppressing a flame without the spiral insert, and actually enhances the flame when the partial pressure fraction is 8 %. The CF_3I causes a transition to a detonation at the same partial pressure fraction, producing a combustion wave that travels over 1400 m/s. A partial pressure fraction of 18 % is required for the CF_3I to fully suppress the flame.

The CF_3I reduces the shock wave velocity the best of the three agents for the propane/air mixture as long as the levels do not exceed 4 %, as seen in Figure 43. Beyond 7 %, the CF_3I is the poorest agent, requiring more than 16 % by partial pressure to attenuate the shock wave to less than 400 m/s. By contrast, C_3F_8 attains full suppression when the partial pressure fraction is only 6 %. HFC-125 is in between. The data plotted in Figure 44 are taken with stoichiometric C_3H_8/air mixtures in the 5 m test section without the spiral. FC-218 causes the combustion wave speed to decrease in a monotonic manner, with suppression occurring when the partial pressure fraction is 8 %. Full suppression is attained with HFC-125 at a concentration of 10 %; however, 2 % and 6 % levels of C_2HF_5 strongly enhance the exothermic reaction. The CF_3I is relatively well behaved, but requires the largest amount (on both a molar and mass basis) of the three agents to fully quench the radiation.

2.4.5 Uncertainty Analysis. The measurement results are subject to experimental uncertainties. Because no generally applicable methods exist which would provide a measure of the reliability of the experimental data with absolute certainty, only an estimate of the magnitude of these uncertainties is undertaken. The estimate is affected by the uncertainty of the determination of the independent variables, such as partial pressures of the components constituting the mixtures under investigation, and the dependent variables, such as shock wave amplitudes, and shock/flame time differences serving to determine their velocities.

The uncertainty of the determination of the partial pressure of an agent is affected by the uncertainty of the static pressure transducer which is ± 0.15 % (combined non-linearity, hysteresis, repeatability, and temperature effects); the combined uncertainty of the digital display device which is ± 0.015 %; the uncertainty associated with the purity of the gases which is ± 0.5 %; and the uncertainty associated with the gas component losses due to leaks occurring in the circulation pump

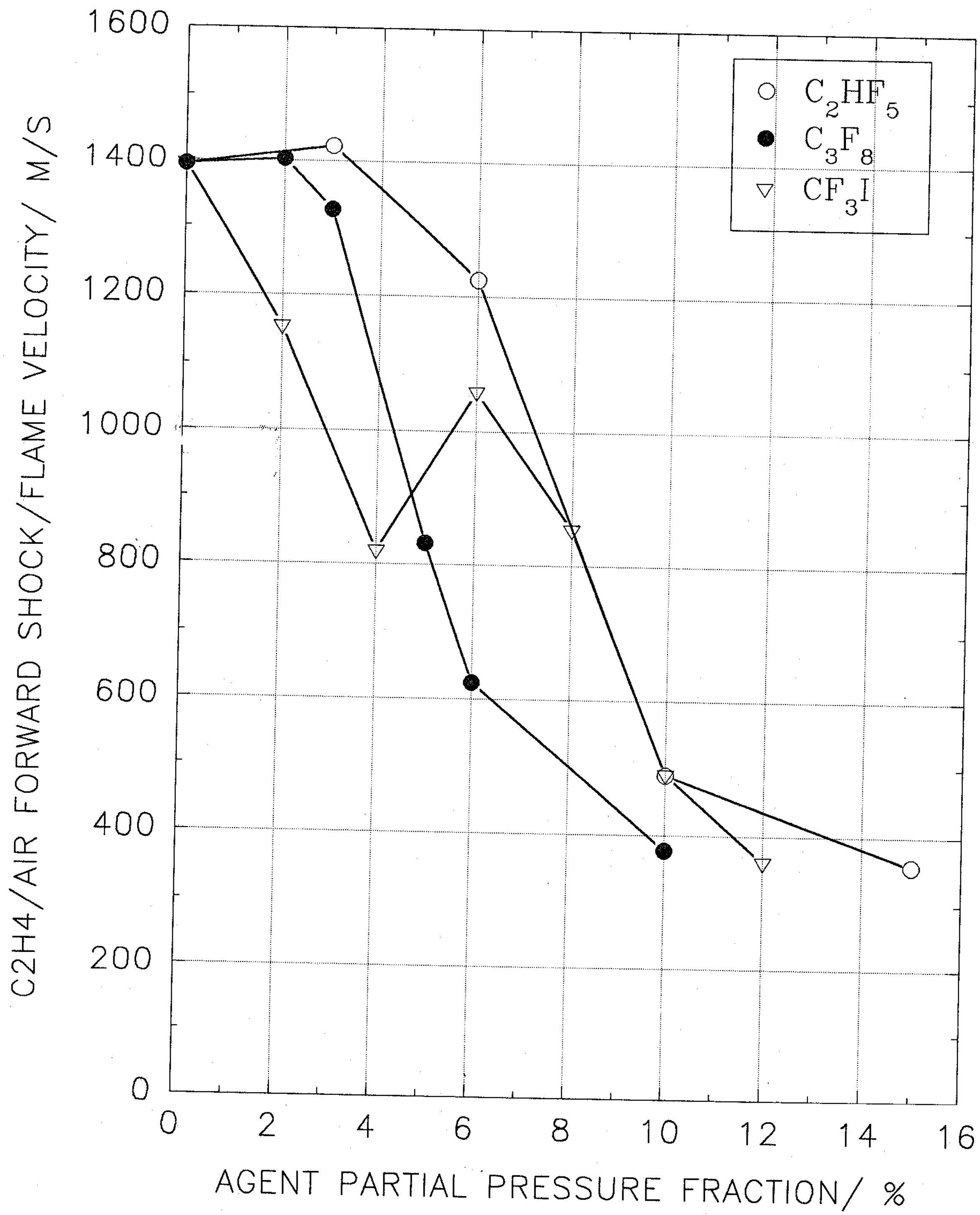


Figure 41. Shock/combustion wave speed in stoichiometric C_2H_4/air mixtures (2.5 m, spiral).

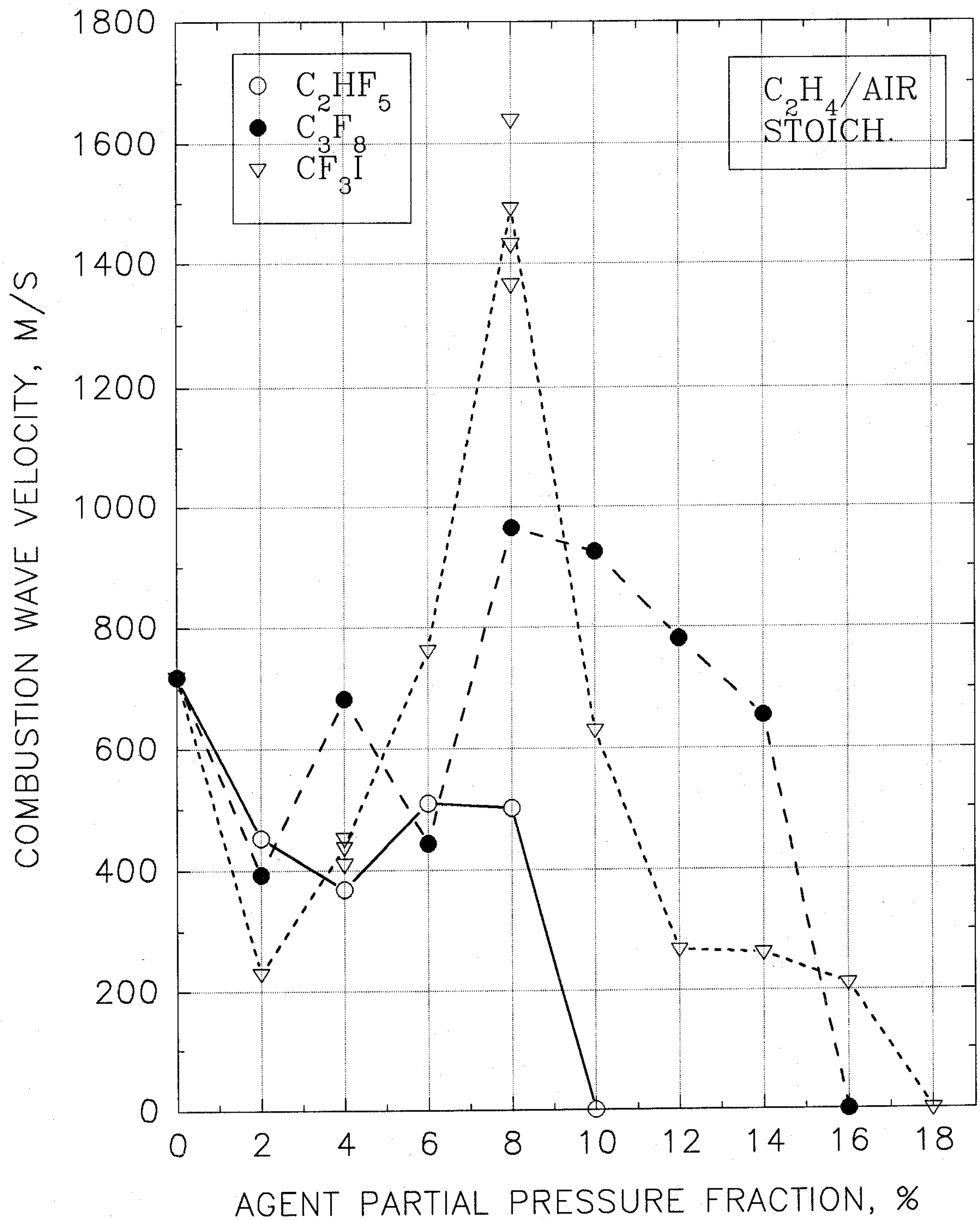


Figure 42. Combustion wave speed in stoichiometric C_2H_4/air mixture (5 m, no spiral).

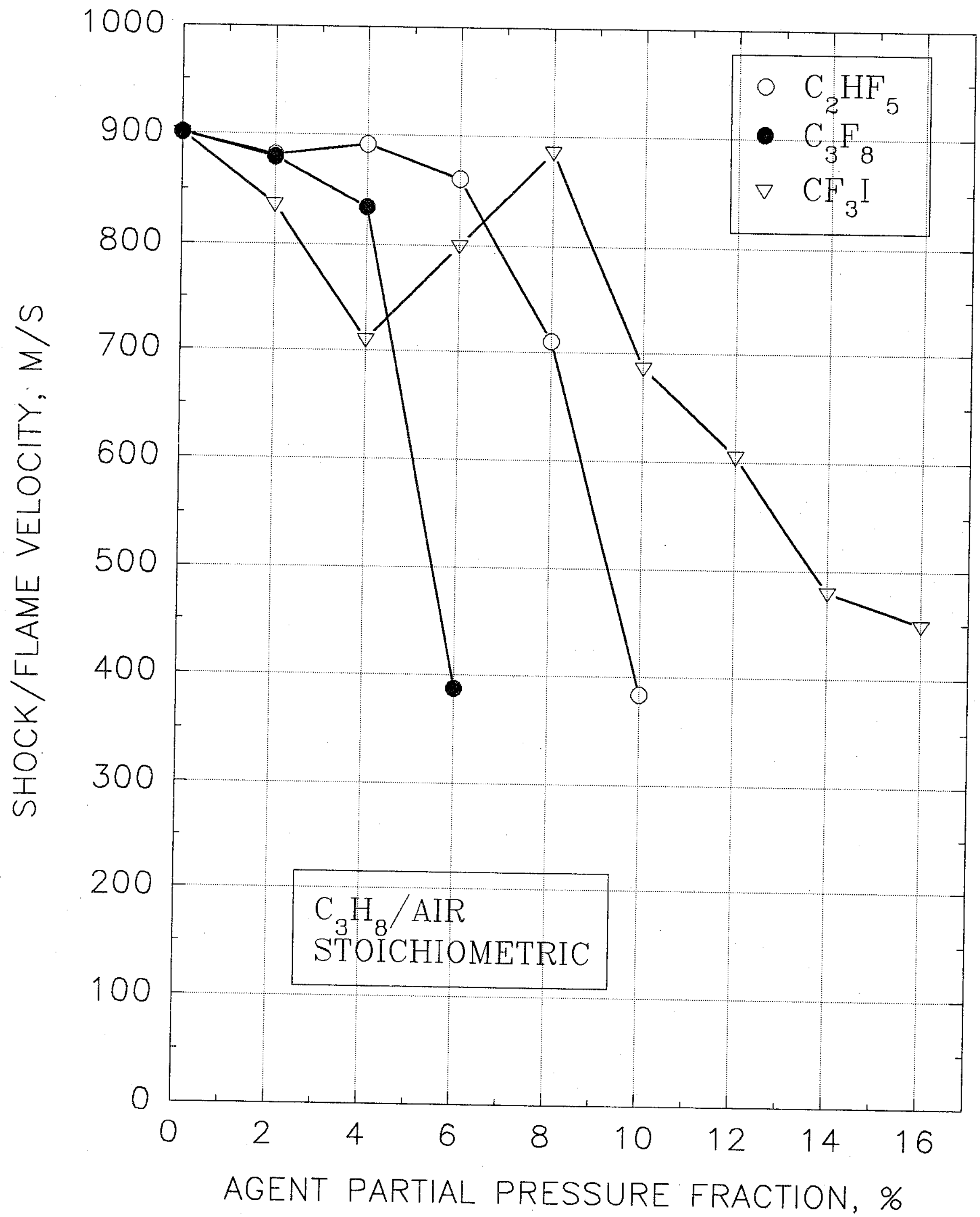


Figure 43. Shock/combustion wave speed in stoichiometric C_3H_8/air mixtures (2.5 m, spiral).

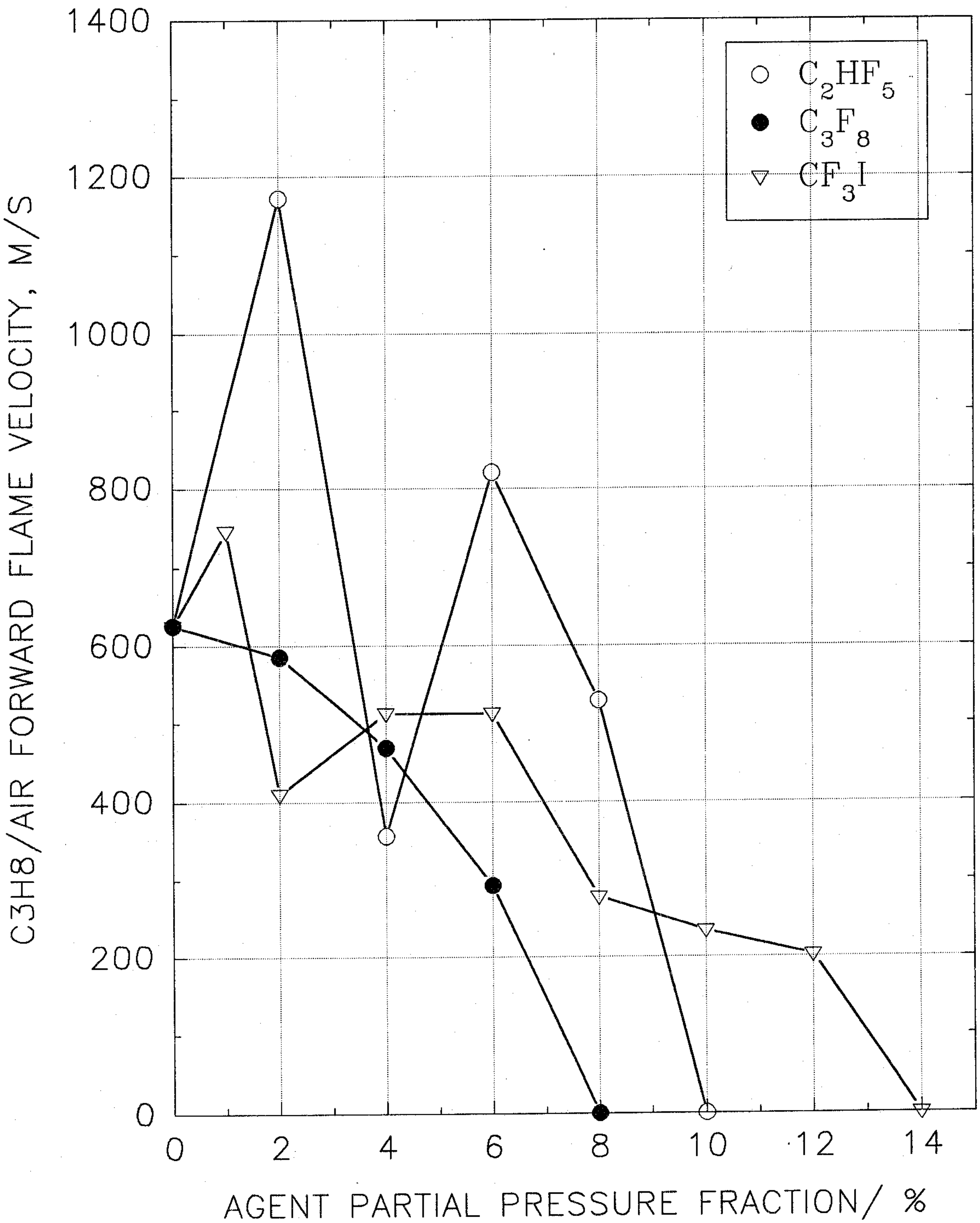


Figure 44. Combustion wave speed in stoichiometric C_3H_8/air mixture (5 m, no spiral).

under operation which is ± 0.3 % (the worst case, assuming that only one component leaks). Combining the uncertainty components by root-sum-of-squares (Taylor and Kuyatt, 1994), the resultant expanded uncertainty of establishing the composition of the mixture is 1.2 % of the reported value.

The determination of the shock wave amplitude is affected by the combined uncertainty of the dynamic pressure transducer, which is ± 1.0 %; the combined uncertainty of the transducer amplifier, which is ± 0.5 %; the combined uncertainty of the digital data acquisition system, which is ± 0.5 %; and the combined uncertainty of the digital readout device, which is ± 0.2 %. The root-sum-of-squares of these uncertainties results in an expanded uncertainty in determining the shock wave amplitude of 2.5 % of the reported value. The uncertainty in the determination of the shock time differences is affected by the some of the same elements and, after considering the differential nature of the measurement and the uncertainty of the readout device (± 0.1 %), can be estimated as ± 3.6 %.

The uncertainty of the determination of the flame time differences is affected by the following factors: the combined uncertainty of the photodiode which is ± 1.0 %; the combined uncertainty of the photodiode amplifier which is ± 0.5 %; the combined uncertainty of the digital data acquisition system which is ± 0.5 %; the combined uncertainty of the digital readout device which is ± 0.1 %. The resultant expanded relative uncertainty in the differential measurement of flame velocity is ± 3.5 %.

The precision of the experimental measurements can readily be determined by observing the agreement between the numerical values obtained in a series of measurements performed in exactly the same way and under the same conditions. Depending on the interpretation of experimental results, either the mean value and the standard deviation is of importance, or the mean value and the maximum absolute deviation is of interest. In the present study it seems that the latter is more meaningful because it indicates the worst possible case that could occur in reality. However, here, both the standard deviation and the maximum absolute deviation are presented as an illustration. The precision of the measurements in these experiments is affected by the following factors: preparation of the compositions of the mixtures; circulation/homogenization of the mixtures; opening of the gate valve; ignition event; formation/propagation of the flame/shock; vibrations of the spiral insert; and ambient temperature changes (± 2 °C). Ambient air pressure and humidity changes do not affect the results as air is supplied from a gas cylinder.

As an example experimental point, the 8 % of CF_3I in the stoichiometric 6.5 percent ethene/air mixture without the spiral insert is analyzed in more detail. For this case, four experiments are taken into account (it is necessary to treat the analysis as very much approximate as from the statistical point of view it would be required to include more experimental points). The means of flame/shock velocities and pressure ratio are 1484, 1635 m/s and 32.5, respectively; the maximum absolute deviations of flame/shock velocities and pressure ratio are 157, 15.2 m/s and 0.97 respectively; the maximum relative deviations of flame/shock velocities and pressure ratio are 10.6, 0.9 and 3.0 % respectively; the population standard deviations of flame/shock velocities and pressure ratio are 101, 8.7 m/s and 0.61 respectively; and the sample standard deviations (as the number of experiments here is less than 20) of flame/shock velocities and pressure ratio are 117, 10.1 m/s and 0.70 respectively (the expanded uncertainties are 233, 20.2 m/s and 1.4). This gives an idea on the precision of the experimental results obtained with the detonation/deflagration tube facility.

2.5 Summary of Results

The fire threat discussed in this section results from a premixed, uninhibited turbulent flame accelerating into a quiescent, premixed, inhibited fuel/air mixture. The response of this highly dynamic situation to different suppressants is sensitive to the fuel, stoichiometry and geometry in the test section, as well as to the amount of agent used. A successful agent mixture would quench the combustion wave, as evidenced by the disappearance of visible radiation, and diminish the speed and pressure build up across the incident shock wave. However, even with 100 % nitrogen in the test section, a residual shock wave will persist. Short of complete suppression, an agent which reduces the combustion and shock wave speeds and minimizes the pressure increase is desired.

Twelve alternative agents to halon 1301 for protection of aircraft dry bays were ranked previously according to how well each could suppress a laboratory turbulent spray flame and a quasi-detonation (Grosshandler *et al.*, 1994). The experiments were designed to cover the range of conditions that might occur following the penetration by an incendiary device of a fuel cell adjacent to a dry bay. High over-pressures (37:1) were measured when HFC-125 was used to suppress a lean C_2H_4/air quasi-detonation. The range of initial conditions that lead to a worsening of the situation rather than a lessening of the threat has been investigated in the current study.

The detonation/deflagration tube facility was modified to operate over a less severe range of conditions. Pressure ratios below 9:1 were generated routinely for lean, stoichiometric and rich mixtures. These lower pressures were achieved by removing the spiral insert in the test section and by replacing the more reactive ethene with propane, which is also a better simulant of vaporized jet fuels. The flame speed was monitored close to the entrance of the test section to better assess the immediate impact of the suppressant on the flame. Previously, incident shock speeds over 1500 m/s were recorded. The current experiments with propane as fuel yielded uninhibited flame speeds between 300 m/s and 600 m/s, much closer to the hundreds of meters per second estimated to occur in the full-scale dry bay experiments. A further modification to the facility has been the doubling of the test section length, to 5 m, which has increased the time available for the incident shock to reflect back into the turbulent flame front. This arrangement has allowed the incident shock speed and pressure ratio, the turbulent flame speed, and the conditions behind the reflected shock wave all to be monitored. The reflected shock wave was always found to be stronger than the incident wave, and, with no agent present in the test section, led to a detonation for a range of initial stoichiometries. Thus, with a single shot, we were able to observe the performance of the suppressant under moderate and highly dynamic conditions.

Table 2 summarizes the results of all the detonation/deflagration experiments done with the three agents in this and the earlier NIST study. The suppression conditions are defined as the partial pressure of agent in the test section necessary to either totally quench the radiation from the reactants or to reduce the pressure ratio to the value had 100 % nitrogen been used. The peak pressure ratios and reaction wave speeds refer to the maximum in the plots of pressure ratios (or velocities) versus agent partial pressure fractions. The agent percent is the partial pressure fraction where the maximum is reached. In most cases, small amounts of agent increased the pressure and reaction wave velocity. A value of 0 % implies that the maximum is attained solely at the uninhibited condition. Generally speaking, the ethene quasi-detonation requires considerably more agent to extinguish than the turbulent propane flame; the stoichiometric mixtures require more agent than either rich or lean conditions; C_3F_8 (FC-218) requires the lowest partial pressure fraction to totally suppress both quasi-detonations and turbulent flames; C_2HF_5 (HFC-125) is the least effective suppressant of a quasi-detonation; and CF_3I is the least effective compound for total suppression of stoichiometric and rich turbulent propane flames. The highest pressure ratio observed was for the lean ethene quasi-detonation with 6 % C_2HF_5 added. HFC-125, when added to the stoichiometric turbulent propane flame at a partial pressure fraction of 2 %, greatly accelerated the speed of the reaction wave, but did little to enhance the pressure build up.

The exact conditions that are likely to exist in a dry bay prior to a fire or explosion are impossible to control. Unfortunately, the relative behavior of the three agents under investigation is strongly dependent upon the initial conditions, causing one chemical to be clearly superior under one arrangement and the same chemical to perform poorly in another. There are some general statements

Table 2. Summary of Experimental Results in Detonation/Deflagration Tube

Parameter	Agent	Fuel and Equivalence Ratio					
		Ethene[a] $\Phi = 0.75$ Quasi-detonation	Ethene[a] $\Phi = 1$ Quasi-detonation	Ethene[a] $\Phi = 1.25$ Quasi-detonation	Propane[b] $\Phi = 0.86$ Turbulent Flame	Propane[b] $\Phi = 1.0$ Turbulent Flame	Propane[b] $\Phi = 1.25$ Turbulent Flame
Maximum Pressure Ratio[c] (@ partial pressure %)[d]	none	18 (0%)	26 (0%)	35 (0%)	8.1 (0%)	8.8 (0%)	8.3 (0%)
	N_2	2.5 (100%)	3.5 (100%)	g	4.5 (100%)	4.6 (100%)	4.5 (100%)
	C_2HF_5	37 (6%)	29 (6%)	35 (0%)	8.5 (4%)	8.8 (2%)	8.3 (0%)
	C_3F_8	24 (2%)	33 (2%)	37 (2%)	8.2 (2%)	9.5 (2%)	8.5 (2%)
	CF_3I	21 (6%)	27 (6%)	35 (6%)	8.1 (0%)	8.8 (0%)	8.3 (0%)
Maximum Reaction Wave Speed[e], m/s (@ partial pressure %)[d]	none	1170 (0%)	1400 (0%)	1530 (0%)	330 (0%)	620 (0%)	510 (0%)
	N_2	0 (100%)	0 (100%)	g	100 (100%)	100 (100%)	50 (100%)
	C_2HF_5	1170 (0%)	1410 (3%)	1530 (0%)	510 (2%)	1180 (2%)	510 (0%)
	C_3F_8	1250 (2%)	1400 (2%)	1530 (0%)	460 (2%)	620 (0%)	510 (0%)
	CF_3I	1170 (0%)	1400 (0%)	1530 (0%)	450 (1%)	740 (1%)	590 (1%)
Suppression Partial Pressure Percent[f]	N_2	40%	g	g	g	g	g
	C_2HF_5	13 to 15%	13 to 15%	13 to 15%	7.5 to 8%	9 to 10%	5 to 6%
	C_3F_8	8 to 10%	> 10%	> 10%	5 to 6%	7 to 8%	3 to 4%
	CF_3I	> 10%	> 12%	13 to 14%	5.5 to 6%	13 to 14%	7 to 8%

[a] 2.5 m test section, with spiral insert, measurement location 2.2 m into test section
[b] 5.0 m test section, without spiral insert, measurement location 0.3 m into test section
[c] ± 5% of value relative uncertainty
[d] ± 1% absolute uncertainty, and note that 0% implies no enhancement over zero inhibitor conditions
[e] ± 11% of value relative uncertainty
[f] ± 1% absolute uncertainty, based upon no flame radiation or pressure ratio equal to value attained by 100% N_2
[g] no data available

that can be made, though. For example, obstacles in the test section lead to higher shock pressure ratios and initial velocities; ethene/air mixtures lead to higher shock pressure ratios and initial velocities; a residual shock wave remains even when the combustion wave is extinguished; and the speed of the combustion wave without obstacles in the flow responds to the agents in a more chaotic manner than the shock pressure ratio.

The impact of these statements are reflected in Figures 45, 46 and 47 for HFC-125, FC-218 and CF_3I, respectively, in an attempt to identify the best overall chemical for an uncertain application. The response parameter, Ψ, is defined as

$$\Psi \equiv \frac{x - x*}{x_0 - x*}$$

where x_0 is the value of the parameter of interest (combustion wave speed, shock speed, or shock pressure ratio) when no agent is present and x* is the corresponding value when extinction has occurred. A value of unity for Ψ means that the agent has no beneficial impact on the combustion process; $\Psi > 1$ implies the agent exacerbates the situation; a performance parameter near zero is desirable, indicating close to total suppression. The volume percents plotted on the abscissa in Figures 45 through 47 are identical to the partial pressure fractions for ideal gas mixtures. This is a reasonable approximation for the close-to-ideal mixtures under investigation in this work. The volume percent of agent is also a more conventional way to compare the performance of different compounds.

Each point in Figures 45 through 47 represents one measured parameter for an individual experiment. For most of the experiments, the normalized radiation wave speed (determined from the photodiodes) and the normalized shock speed and pressure ratio (measured with the piezoelectric transducers) are plotted. The averages of Ψ are shown as the dotted lines in Figures 45 through 47. The individual values exceed 2.5 (the maximum plotted) for a few of the experiments using C_2HF_5 and CF_3I. These data are not shown in the Figures but were included when the averages of Ψ were computed. By comparing the three curves one gets an indication of general trends, and where one agent is likely to out-perform another.

Examining Figure 45, one sees that the HFC-125, on average, cuts the magnitude of the deflagration/detonation threat in half when its volume fraction is greater than about 8 %. FC-218 (Figure 46) achieves the same level of protection for volume fractions greater than 5 %, while a volume fraction of almost 9.5 % is required of CF_3I to reduce the combustion activity to half (Figure 47). All three agents **increase** the threat for lesser levels. The HFC-125 leads to pressures and wave speeds higher by a factor of 1.8 at volume fractions near 5 %. The FC-218 and CF_3I produce close to a 50 % overshoot when the volume fractions are 2 % and 5 %, respectively. The CF_3I is much more chemically reactive than the other agents, undergoing three transitions between suppression and enhancement as its concentration is increased. A 90 % reduction in the threat requires 14 % CF_3I, 13 % FC-218, and 11 % HFC-125 by volume. Total extinction of the exothermic reaction under all conditions examined in this study requires volume percentages greater than 20 %, 18 % and 16 %, respectively, of CF_3I, FC-218 and HFC-125.

As a benchmark, about 6 % (vol.) of CF_3Br was required to reduce the pressure build-up by 90 % in the earlier NIST study (Grosshandler *et al.*, 1994). This implies that almost three and a half times as much liquid FC-218 is necessary for equivalent protection, while about two and one half times liquid CF_3I must be stored. With this measure of performance the HFC-125 appears to require the least liquid storage of the three halon alternatives tested, requiring just over twice the liquid volume of CF_3Br.

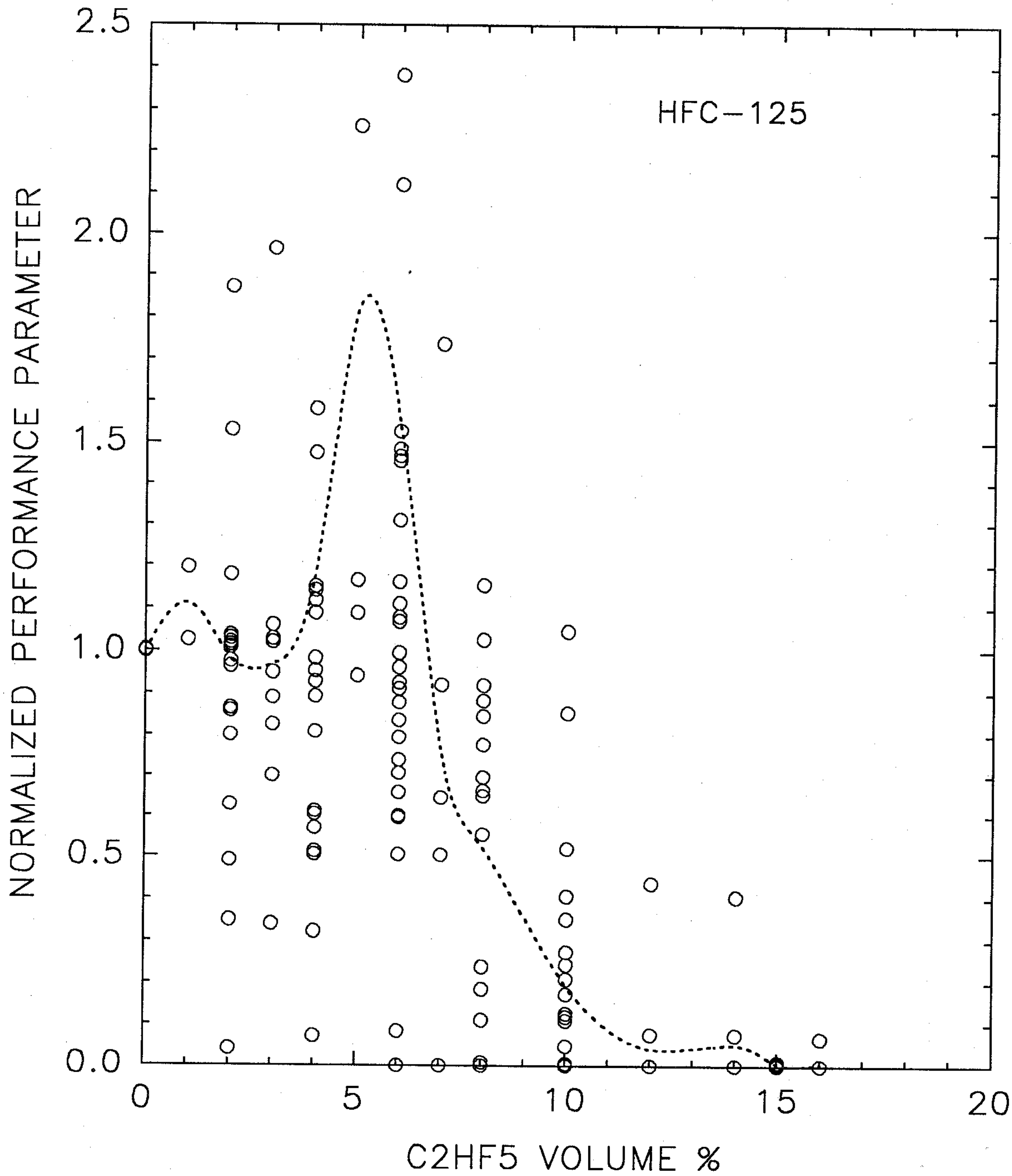


Figure 45. Performance parameter vs. volume fraction of HFC-125 (C_2HF_5).

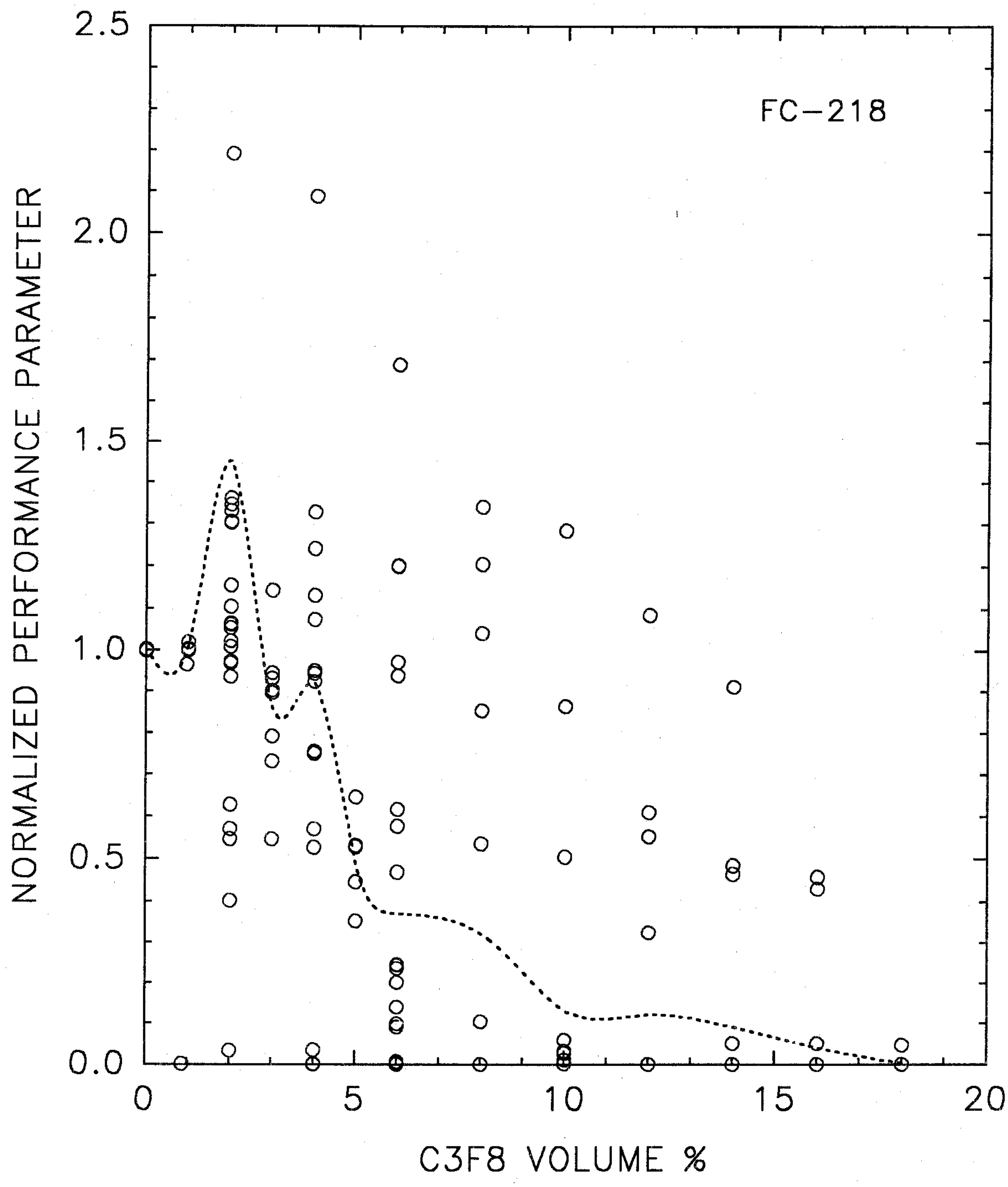


Figure 46. Performance parameter vs. volume fraction of FC-218 (C_3F_8).

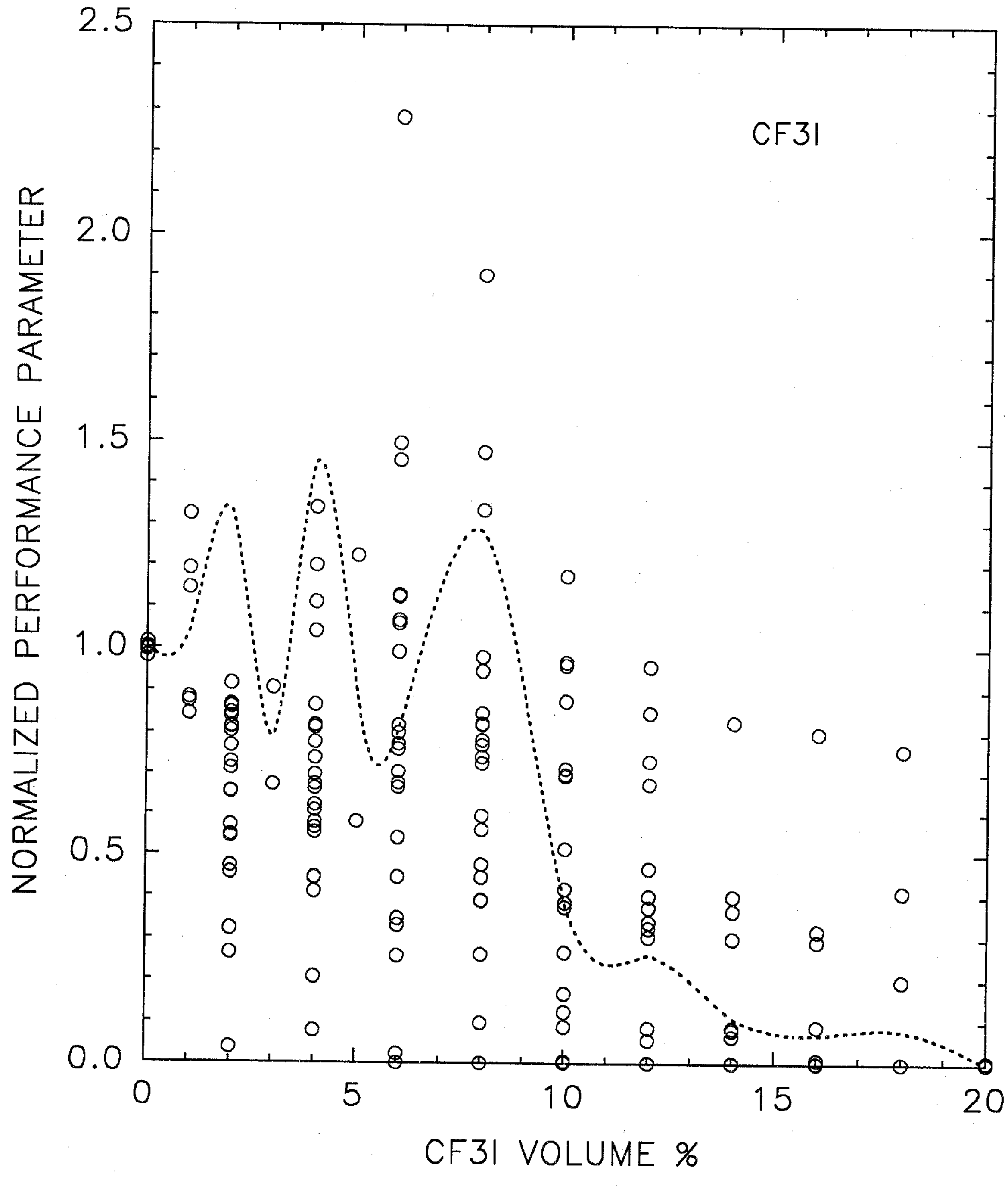


Figure 47. Performance parameter vs. volume fraction of CF_3I.

2.6 Conclusions

The following conclusions are made based on the results obtained:

a. Combustion and suppression processes in premixed hydrocarbon/air systems under highly dynamic conditions can be more effectively studied in the **modified** two-sectional tube, permitting clear discrimination of the combustion modes and performance among various gaseous extinguishing compounds.

b. There is a significant difference in combustion behavior between propane/air and ethene/air mixtures: the combustion modes at higher velocities overlap totally in the ethene/air mixture for the two geometric configurations while the propane/air mixture is characterized by a clear separation between the combustion modes for the two arrangements. Also, the regime of equivalence ratios for which combustion is detectable in the tube is much broader for the ethene/air mixture. Furthermore, a detonation was unable to develop in the propane/air mixture when the spiral insert was taken out of the tube.

c. The ethene/air flame in the quasi-detonation wave under suppression very closely follows the shock wave with the same velocity. The distance between the flame and the shock increases with the amount of an extinguishing agent. At extinguishment, the flame disappears, while the residual shock still exists.

d. The presence of a hydrogen-containing suppressant in the ethene/air mixture results in a significant increase in pressure ratio relative to that for the pure combustible mixture. The phenomenon occurs also for the compounds not containing hydrogen atoms at relatively lower concentrations. The impact is generally weaker for stoichiometric and rich mixtures than it is for lean mixtures.

e. C_3F_8 is the most effective extinguishing compound in suppressing and attenuating flame/shock systems in the lean, stoichiometric, and rich ethene/air mixtures under highly dynamic conditions in the detonation/deflagration tube.

f. Depending on their concentrations, the presence of the three extinguishing compounds in the propane/air mixtures causes the combustion either to be enhanced or suppressed, often with complex extrema exhibited. The behavior is diminished, however, when the mixture becomes richer in fuel content.

g. CF_3I is the best agent for attenuating shock pressure ratio in the lean, stoichiometric and rich propane/air mixtures. Such performance may be attributed to the significant endothermicity of the decomposition process of CF_3I during the passage of the shock through the mixtures under investigation.

The bottom line is, the conclusions drawn from the previous NIST study have been confirmed. FC-218 provides the most consistent performance over the widest range of fuel/air mixtures and tube geometries. The CF_3I has the greatest positive impact at low partial pressure fractions, but exhibits non-monotonic behavior of flame speed and shock pressure ratio at increasing concentrations. The dangerously high over-pressures previously exhibited by HFC-125 were not observed during suppression under more moderate (and likely) combustion conditions. Based upon the results from this section alone, none of the three agents can be eliminated from consideration as candidates for dry-bay applications.

2.7 Acknowledgments

This research was supported by the U.S. Naval Air Systems Command and the U.S. Air Force, Wright Laboratory. Wing Tsang, Anthony Hamins and Valeri Babushok of NIST are gratefully acknowledged for helpful discussions during the course of this work. The contribution of Wendy Chien to the experimental phase of this work is highly appreciated. Richard Thorpe, Science Applications International Corporation, is gratefully acknowledged for his editorial contribution.

2.8 References

Baker, W.E., Cox, P.A., Westine, P.S., Kulesz, J.J. and Strehlow, R.A., *Explosion Hazards and Evaluation*, Elsevier, 1983.

Bennett, M., Survivability Enhancement Branch, Wright-Patterson AFB, personal communication, 1993.

Carbaugh, S.G., Survivability Enhancement Branch, Wright-Patterson AFB, Minutes of T2 Meeting, October 14, 1993.

Chapman, W.R. and Wheeler, R.N.V., "The Propagations of Flame in Mixtures of Methane and Air. Part IV. The Effect of Restrictions in the Path of the Flame," *Journal of the Chemical Society*, London, p. 2139 (1926).

Gmurczyk, G., Grosshandler, W., Peltz, M. and Lowe, D., "A Facility for Assessing Suppression Effectiveness in High Speed Turbulent Flames," *Eastern States Section Conference*, The Combustion Institute, Princeton, 1993.

Gmurczyk, G.W., Grosshandler, W.L., and Lowe, D.L., "Suppression Effectiveness of Extinguishing Agents under Highly Dynamic Conditions," *Fire Safety Science - Proceedings of the Fourth International Symposium*, T. Kashiwagi, ed., International Association of Fire Safety Science, USA, pp. 925-936, 1994.

Gmurczyk, G., and Grosshandler, W., "Suppression of High-Speed Flames with C_1-Halocarbons," *Twenty-fifth Symposium (International) on Combustion*, The Combustion Institute, in press, 1995.

Grosshandler, W.L., Gann, R.G., and Pitts, W.M., editors, *Evaluation of Alternative In-flight Fire Suppressants for Full- scale Testing in Simulated Aircraft Engine Nacelles and Dry Bays*, NIST Special Publication 861, Gaithersburg, April 1984.

Lee, J.H.S., "Fast Flames and Detonations," *Chemistry of Combustion Processes*, The American Chemical Society, 1984.

Lee, J.H., Knystautas, R. and Chan, C.K., "Turbulent Flame Propagation in Obstacle-filled Tubes," *Twentieth Symposium (International) on Combustion*, The Combustion Institute, pp. 1663-1672, 1984.

Lefebvre, M.H., Nzeyimana, E., Van Tiggelen, P.J., "Influence of Fluorocarbons on $H_2/O_2/Ar$ Detonations Experiments and Modeling," *Progress in Astronautics and Aeronautics*, AIAA, 1992.

Nettleton, M.A., *Gaseous Detonations: Their Nature, Effects and Control*, Chapman and Hall, 1987.

Peraldi, O., Knystautas, R. and Lee, J.H., "Criteria for Transition to Detonation in Tubes," *Twenty-first Symposium (International) on Combustion*, The Combustion Institute, pp. 1629-1637, 1986.

Sheinson. R.S., Penner-Hahn, J.E., and Indritz, D., 1989, "The Physical and Chemical Action of Fire Suppressants," *Fire Safety Journal* ***15***, pp. 437-450.

Taylor, B.N., and Kuyatt, C.E., *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, Gaithersburg, September 1994.

Westbrook, C.K., "Chemical Kinetics of Hydrocarbon Oxidation in Gaseous Detonations," *Combustion and Flame 46*, 191 (1982).