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Dautriche — Shock Tube Measurement of High Propagation Rates in Pyrotechnic Materials

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Introduction

There are times when it is of interest to measure propagation rates in highly energetic pyrotechnic materials, such as flash powder. These rates tend to range from less than 1000 to about 5000 feet per second. Conventional means of making such velocity of propagation (VOP) measurements involve the application of techniques developed for use with high explosives in order to make velocity of detonation (VOD) measurements. Some examples of the equipment used are high speed framing cameras, streak cameras, continuous velocity probes, and any of the various so-called "pin" techniques. These approaches require expensive instruments and in some cases may not be entirely reliable in the lower reaction pressure regime of pyrotechnics, especially when weakly confined.[1,2,3]

In searching for an inexpensive alternative for making pyrotechnic VOP measurements, and after attending a seminar by Chris Cherry[4] dealing with some novel applications of Nonel shock tube, the authors have developed a method using shock tube. The method is based on the old Dautriche method for making VOD measurements.

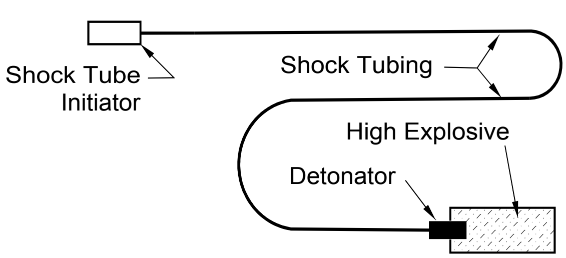

Figure 1. Shock tube initiation system for high explosives.

Shock tube systems, such as Nonel Trunkline from Ensign-Bickford, are non-electric initiation systems for high explosives (see Figure 1). The basic component is a thin tube (1/8-inch OD), which has a very thin inner coating[5] (≈one pound per 100,000 feet) of a mixture of aluminum metal powder and HMX, a high explosive. When subjected to simultaneous application of heat and pressure, as can be provided by a shotgun primer, a shock wave initiates and propagates along the inside of the tube at about 6500 feet per second, according to Ensign-Bickford's technical bulletin.[5] However, according to their Technical Services personnel, the actual rate is somewhat greater, and maybe subject to environmental conditions and other factors such as length. Passage of the shock wave normally leaves the tube intact and essentially unaffected, except for the barely detectable appearance of a carbony film on its inner surface. However, in the event that a shock wave is initiated at both ends of the tube, the point where the waves collide is evidenced by a small rupture (burst) of the tube at that point. The cost of Nonel shock tube is about $0.04 per foot in large quantities. It can be shipped as a non-hazardous material (plastic tubing, NOS). [See References 5 and 6 for more information concerning non-electric shock tube, and Reference 7 for a discussion of the channel effect, which is the basis of operation of shock tube.]

The Dautriche (D'Autriche) method for measuring detonation velocity pre-dates the availability of high-speed cameras and digital electronics. It involves the use of detonating cord (detonating fuse, det-cord, prima-cord), and is illustrated in Figure 2. In essence, two ends of a piece of detonating cord are inserted some distance apart into a column of high explosive, such as a stick of dynamite. When the

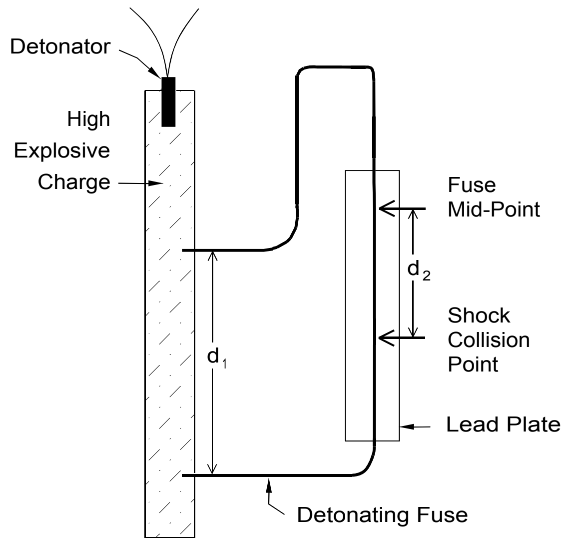

Figure 2. Dautriche method for measuring detonation velocity.

explosive is detonated, the shock wave propagates along its length, first encountering and initiating one end of the detonating cord. Then, after the shock wave in the explosive has propagated further, it encounters and initiates the other end of the detonating cord. At this time there are two shock waves propagating along the detonating fuse, one from each end. If the detonating fuse has been laid along the surface of a lead plate, the point where the two shock waves eventually collide will be witnessed by the lead plate as a point of increased deformation. If the VOD of the detonating cord, the distance between the points where the cord was inserted into the explosive column, and the distance from the mid point of the cord to the point of collision of the two shock waves, are all known, then the unknown VOD of the explosive column can be calculated using Equation 1. [See References 8 or 9 for more information on the Dautriche method.]

$$D_u = D_f\,(d_1/2d_2) \qquad (1)$$

where

D_u is the unknown VOD of the column of explosive,

D_f is the VOD of the detonating fuse,

d_1 is the distance along the column of explosive between points of attachment of the detonating fuse, and

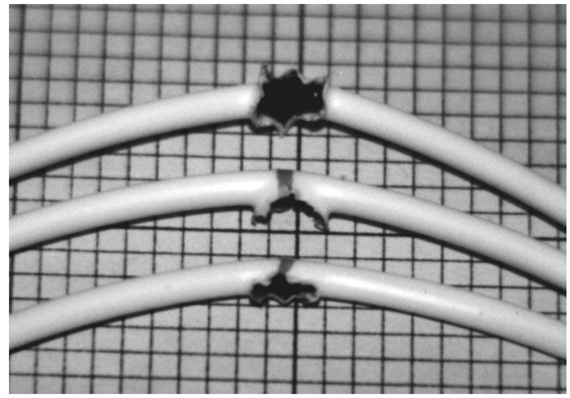

Photo 1. Pieces of Nonel Shock Tube, illustrating the rupturing (bursts) caused by the collision of two shock waves.

d_2 is the distance from the midpoint of the detonating fuse to where the shock waves meet.

There are a number of reasons why the Dautriche method is poorly suited for use with pyrotechnic materials. Most importantly, pyrotechnic materials generally do not produce the shock pressures needed to initiate detonating fuse. However, even if this were somehow overcome, the expense and effort required with the use of lead plates, and explosive output from the detonating fuse, make the Dautriche method less than desirable.

Shock Tube Method of VOP Measurement

For the most part, pyrotechnic VOP measurements can be made by simply substituting shock tube for detonating cord in the Dautriche method, but without the lead plate. The point of collision of the two shock waves is indicated by the burst point of the tube. Examples of this are shown in Photo 1. To allow measurement of the collision point from the center of the length of the shock tube, it is important to mark the midpoint on the tube before the explosive is initiated, since the explosion may destroy a short section of shock tube at each point of attachment to the explosive column.

It is possible that the migration of small amounts of loose powdered explosive mixtures into the open end of the shock tube at its point of attachment, could introduce errors into the

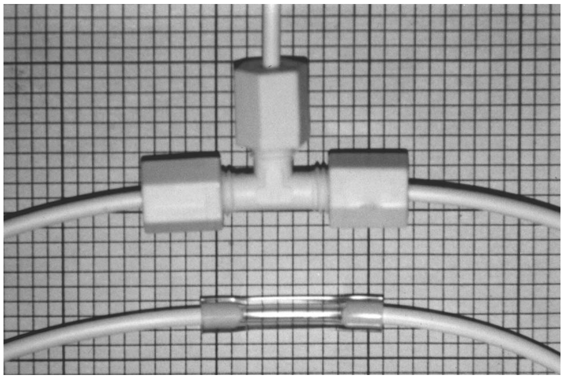

Photo 2. Coupling methods for shock tube; a straight coupling using Tygon tubing as a sleeve, and a three-way coupling using a plastic tee.

measurement. This can be avoided by placing a small piece of 1-mil polyethylene film over the end of the shock tube before it is attached to the tube, which will eventually contain the explosive charge. (In these experiments the tubes used to contain the explosive charge were convolute tubes made of kraft paper.) In attaching the shock tube to the empty paper tube, hot-melt glue has proven to be effective.

The VOP in the pyrotechnic explosive charge may not be constant and the reaction front is likely to have an irregular and changing shape as it moves along the charge. Thus, it is desirable to have the benefit of several VOP measurements along the length of the charge. This can be accomplished by using any number of lengths of shock tube attached along the explosive. However, because of operational difficulties, it is undesirable to have all the lengths of tube attached at the time the paper tube is filled with the explosive being studied. This problem can be largely eliminated and the number of attachment points reduced to nearly half, by taking advantage of another characteristic of shock tube.

Pieces of shock tube can be joined by merely inserting both ends into a sleeve made of material such as Tygon tubing. Also the ends need not be in direct contact with one another (i.e. the shock wave can successfully jump an inert gap and reestablish itself in the continuing shock tube). This allows interesting and useful possibilities in joining and fanning shock tube.[4,6] For example, one piece of tube can successfully

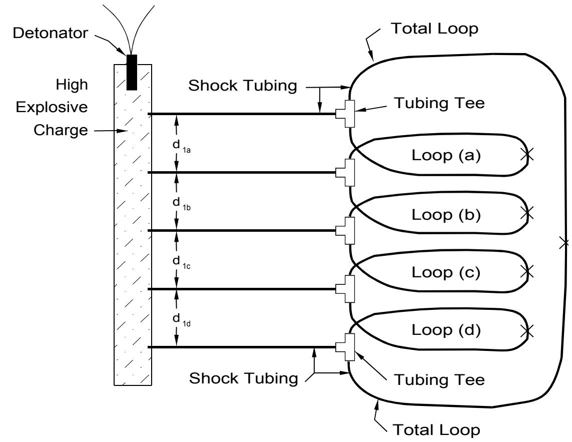

Figure 3. Shock tube method for measuring propagation velocity.

pass a shock wave to two pieces of tube by using a 1/8-inch tubing tee such as might be purchased in a hardware store. Photo 2 illustrates such an arrangement using a plastic tee from a laboratory supply house. It is important to note that when a propagating shock wave encounters an inert gap, such as inside a tee, the strength of the wave weakens causing its velocity to be reduced. A distance of perhaps a foot may be required before the shock wave regains a steady state velocity.[4] Thus, in order to get accurate results, it is necessary to use a symmetric setup, so that delays, introduced when the shock waves cross gaps, will cancel.

The problem of having numerous long lengths of shock tube attached to the paper tube when loading the explosive, can be reduced by initially only attaching a series of relatively short lengths of shock tube. Then after the paper tube has been loaded with the pyrotechnic explosive, tees can be attached to the already installed short lengths of shock tube and other lengths of shock tube (with their mid-points marked) can be attached between the tees. This is shown schematically in Figure 3. (Not shown in Figure 3 is a barrier used to protect the tees and shock tube loops from damage when the device is exploded.) When the pyrotechnic explosive is initiated, and the reaction front reaches the first shock tube attachment point, a shock wave begins to propagate down that tube. When the shock wave enters the tee it initiates shock waves in both pieces of the shock tube

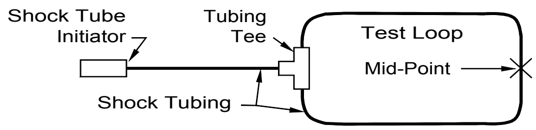

Figure 4. Timing consistency determination for shock tube method.

attached to the tee. One piece is the beginning of loop(a) and one piece is the beginning of a loop for the total length of explosive. This provides a measurement of the VOP for the total length of explosive. It also provides the needed symmetry to be certain that the timing of the passage of the shock wave through the first tee will be the same as for all subsequent tees. A little later, when the reaction front in the pyrotechnic explosive reaches the second shock tube attachment point, a shock wave begins to propagate down that tube. At the tee on that line, shock waves are initiated on the end of loop(a) and the beginning of loop(b). At this time, provided loop(a) is sufficiently long, there will be two shock waves moving along it from opposite ends. The point where the two waves eventually meet will be revealed by a burst point (see Photo 1). In this same way, as the pyrotechnic reaction front passes through the explosive charge, pairs of shock waves are initiated in each of the succeeding loops. At the completion of the experiment, after the explosive charge has been consumed, the lengths of shock tube are collected and the distance from each mid-point to its respective burst point is measured. Finally, using Equation 1, the average VOP between each pair of attachment points is calculated.

Results

Before VOP measurements were made it was appropriate to first verify the reproducibility of the timing that could be achieved. This was a concern because the method relies on there being a fairly constant and reproducible time between the entry of a shock wave into the tee and the initiation of shock waves in both pieces of tube connected to it. One set-up used to examine this is shown schematically in Figure 4. The shock initiator in this case was a .22 caliber starter pistol, with the shock tube in close proximity to the end of the blank cartridge. The mid-point of the loop had been marked, and, after firing, the distance to the burst point in the shock tube was measured. In a series of five tests, the burst point was never more than 0.04 inch (1 mm) from the mid-point mark. Thus, it would seem that the time of passage of the shock wave was always essentially equal through both legs of the tee.

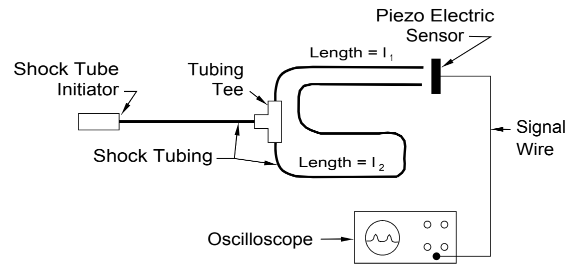

Figure 5. Determination of shock velocity within shock tube.

The quoted rate of propagation through Nonel shock tube was known to be an understatement of its true speed. Also, the actual speed was known to be somewhat dependent on conditions, such as length of shock tube, temperature, pressure, etc. Thus it was appropriate to measure its speed under conditions similar to those anticipated during the experiments. The apparatus used to accomplish this, is shown schematically in Figure 5. The shock tube set-up is similar to that in Figure 4; however, in this case the test loop was cut and the ends positioned just above the surface of the piezoelectric sensor. This sensor produces a current pulse whenever a pressure wave impacts the sensor. In each test, the shorter length (l_1) was a constant 11.8 inches (30 cm), and the longer length (l_2) was varied in the range expected for future experiments. Because the lengths of the two legs were different, the arrival of the shock waves at the piezoelectric sensor occurred at different times. The difference in arrival times was recorded using a digital oscilloscope. The propagation velocity of the shock tube was calculated using Equation 2.

$$VOP_{st} = (l_2 - l_1)/t_d, \qquad (2)$$

where

VOP_{st} is the velocity of propagation of the shock tube,

l_1 and l_2 are as indicated in Figure 5, and

t_d is the time difference between arrival of the shock waves.

Table 1 is a listing of VOP data for Nonel shock tube. It does not appear that the VOP is length dependent over the range examined, and the average VOP is 7090 feet per second (2.16 mm/μs).

Table 1. Velocity of Propagation Data for Nonel Shock Tube.

Length (l_2) inches (cm)	Time Dif. (t_d) milliseconds	VOP_{Nonel} ft/sec (mm/μs)
129.9 (330)	1.38	7120 (2.17)
169.3 (430)	1.85	7090 (2.16)
198.9 (530)	2.30	7120 (2.17)
236.2 (630)	2.79	7050 (2.15)
	Average	7090 (2.16)

Two attempts were made to use the shock tube method to measure the VOP of a flash powder. In both cases the setup was essentially as shown in Figure 3. The flash powder was 70:30 potassium perchlorate (Chinese) and German Blackhead aluminum. The explosive containing tube was �-inch (1.6 cm) inside diameter with a 5/8-inch (0.32 cm) wall. The flash powder was slightly compacted using gravity by tapping the loaded paper tube on a tabletop; however, the loading density of the powder was not determined. A No. 8 electric detonator (blasting cap) was used to initiate the charge. The results of the two experiments are reported in Table 2.

Table 2. Velocity of Propagation Determinations for a Flash Powder.

Distance (d_1) inches (cm)	Distance (d_2) inches (cm)	VOP_{flash} ft/sec (mm/μs)
Test 1		
0.80 (2.0)	2.64 (6.7)	1060 (0.32)
0.80 (2.0)	2.32 (5.9)	1220 (0.37)
0.80 (2.0)	2.76 (7.0)	1030 (0.31)
0.80 (2.0)	3.66 (9.3)	770 (0.23)
	Average	1040 (0.31)
Test 2		
1.13 (2.9)	3.50 (8.9)	1140 (0.35)
1.04 (2.6)	2.01 (5.1)	1830 (0.55)
0.91 (2.3)	3.39 (8.6)	950 (0.29)
	Average	1270 (0.40)

Conclusion

The results of the above VOP measurements seem reasonable in both magnitude and precision, considering the likely nature of propagation reactions in a flash powder.[2,3,10,11,12] However, more study remains before results from the shock tube method should be considered completely reliable.

The work reported here was completed about a year and a half ago, with no additional measurements made in the interim because of the press of other activities. The authors hope to devote more effort to this study in the future but have chosen to publish these preliminary results for fear that other work will continue to prevent further development of the method and in hope that others may benefit from the work being reported.

Acknowledgments

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