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SHOCK TESTING WITH HIGH EXPLOSIVE INITIATED GAS DETONATIONS*

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Abstract

Pressure pulses from detonating gas mixtures have been successfully used to produce mechanical shock accelerations of test items. Methods of controlling detonation pressures and pulse durations, and resulting test item accelerations, have been investigated in the past; however, another parameter of importance, the pulse rise time, has received little attention in previous work. This paper describes the development of a simple, convenient method of controlling pulse rise times in explosive gas tests.

The pulse rise time on a test item subjected to an explosive pressure loading is a function of the rate or velocity at which the shock wave sweeps over the affected surfaces. The sweep velocity is, in turn, a function of the angle at which the shock wave meets the test item surface.

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The method devised for control of rise times, or sweep velocities, consists of using small strands of solid high explosives to propagate the gas detonation. By properly positioning the explosive strands relative to the test item surface, a wide range of shock pulse sweep velocities is possible. This method lends itself well to large or complex shapes. Strands of explosive are arrayed in a frame at the proper orientation with the test item. The assembly is then placed in a detonation chamber filled with an explosive gas mixture. The HE initiation provides the proper sweep velocity or rise time while the pulse amplitude and duration are controlled by the setup parameters mentioned previously.

Tests to investigate the performance of this method were conducted in four types of setups: (1) frangible wooden chambers; (2) a rectangular steel chamber; (3) a 16-inch diameter, 14-foot long detonation tube; and (4) a 26-inch diameter, 130-foot long tube. The gas mixture ordinarily used was hydrogen and oxygen, with Primacord as the solid explosive.

Experimental results were quite encouraging and generally confirmed predictions. Shock front sweep velocities of as high as 30,000 feet per second were obtained. The results indicate that high explosive initiated gas detonations will provide pressure pulses controllable in amplitude, duration, and rise time for blast load simulation and other shock tests requiring similar pulses.

Introduction

Pressure pulses from detonating gas mixtures have been successfully used to produce mechanical shock loadings of test items.¹ This technique is particularly useful for laboratory duplication of blast loading conditions. Basically, the procedure consists of placing the test item in a tube, gun or other chamber filled with an explosive gas mixture. Detonation of the mixture creates a high velocity shock wave which impinges upon the test item surface. The force exerted by the shock wave generates a shock acceleration pulse, provided the test item is mounted such that it is free to accelerate. Figure 1 shows an idealized acceleration-time history typical of those produced by detonation wave loading.

Three parameters are ordinarily of prime importance in designing a shock test using explosive gases: (1) the peak pressure or acceleration amplitude, (2) the pulse duration, and (3) the pulse rise time. Control of the peak pressure is a relatively simple matter. Both theory and experiment have shown that the peak pressure in a gas detonation wave is essentially a constant multiple of the initial unburned mixture pressure, the value of the constant depending upon the composition of the mixture.²⁻⁷ Almost any desired peak pressure, and corresponding peak acceleration of a test item, may be obtained by varying the initial pressure and composition of the explosive gas

Note: References appear on pages 33 and 34.

mixture. Previous experiments have also shown that pulse durations may be controlled by proper design of the geometry of the setup, particularly the detonation tube length and volume.⁸ However, the third parameter of importance, pulse rise time, has received little attention in previous explosive gas work. Therefore, an investigation was launched to develop a simple repeatable method of controlling the shock pulse rise time on a test item subjected to a gas detonation loading.

Theoretical Development

The pulse rise time on a test item subjected to an explosive loading is defined as the time required for the pressure force to rise from an initial value to its peak value. In general, pressure cannot be applied instantaneously to the entire test item surface. Some finite period of time is required for the detonation wave to sweep over the affected areas. This sweep time corresponds to the rise time of the pressure force. The pressure rise time within the wave front itself is only a fraction of a microsecond and ordinarily will be negligible compared to the time required for the wave to travel over the test item.

Pressure force rise time is therefore seen to be a function only of the rate or velocity at which the detonation wave sweeps over the test item surface, for a test item of a given size and shape. Consequently,

in the following discussion sweep velocity, instead of actual rise time, will be the parameter of interest. Sweep velocity, defined as the rate at which a pressure change engulfs a test surface, may differ considerably from the detonation wave velocity. This will be illustrated by the examples of Figure 2, in which the test item is a simple flat plate.

In Figure 2-(a), the plate surface is parallel to the direction of detonation wave propagation. The sweep velocity (V_S) is then identical to the detonation velocity (V_D). In Figure 2-(b), the plate has been rotated 90 degrees to face directly into the oncoming detonation wave. Pressure will be applied instantaneously over the entire surface; therefore, the sweep velocity is infinite and the rise time zero. Figure 2-(c) illustrates the general case. The surface is oriented at some arbitrary angle (α) to the wave front. Wave velocity (V_D) is the component of sweep velocity (V_S) in the direction of wave travel. The sweep velocity is then found as

$$V_S = \frac{V_D}{\sin \alpha} \quad (1)$$

Another approach which yields the same result is to compute the time required for the wave to travel the length of the test surface projected in the direction of propagation. Referring to Figure 2(c):

$$x_1 = x_2 \sin \alpha \quad (2)$$

$$\text{Also, } x_1 = v_D t \quad (3)$$

where t = sweep time interval.

$$\text{Therefore, } x_2 = \frac{v_D t}{\sin \alpha} \quad (4)$$

$$\text{and } v_S = \frac{x_2}{t} = \frac{v_D}{\sin \alpha} \quad (5)$$

Since the two factors which determine sweep velocity are detonation velocity and detonation wave incidence angle, one might reasonably expect to control sweep velocities by varying either or both of these factors. In actual practice, however, relatively little can be accomplished by attempting to change gas detonation velocities. Detonation velocity is a physical constant of an explosive gas mixture, and practically all known mixtures have velocities which fall within the range of 6000 to 12,000 feet per second.² Consequently, sweep velocities may be varied by a factor of only two at most by using mixtures having different detonation rates. Therefore, the primary means of sweep velocity control must be by control of the detonation wave incidence angle. While this method of control appeared from the beginning to be more versatile and promising, its development was actually dictated by the need for pressure force rise times with sweep velocities well

beyond the maximum velocity of 12,000 feet per second obtainable from a gas detonation alone with incidence angle, α , equal to 90 degrees.

If the test item were a simple flat plate, such as in the example of Figure 2, changing the detonation wave incidence angle would only require rotating the plate. This is not possible with a more complex shape because all parts of the test item would not be at the same angle with the wave front. A method had to be devised to obtain the proper angular orientation of wave front to test item over all affected areas of the test item simultaneously.

The proposed test method consisted of using small amounts of solid high explosives in strands or strips to propagate the gas detonation. As shown in Figure 3, the gas detonation front would propagate outward from the solid explosive strand at the gas detonation velocity while the point of initiation would necessarily propagate at the solid explosive detonation rate. Detonation velocities are normally much higher in solid explosives than in gases; values of 20,000 feet per second or more are common.⁹ The resulting gas detonation wave would form at some angle to the solid explosive strand, the magnitude of the angle being a function of the two detonation velocities.

If the gas detonation is assumed to propagate spherically outward from a point of initiation (point 0 in Figure 3), in some time, t ,

the wave will have traveled a radial distance, r , given by

$$r = V_D t \quad (6)$$

During the same time period the solid explosive detonation has traveled a distance, y , given as

$$y = V_E t \quad (7)$$

where V_E is the detonation velocity in the solid explosive. The angle, ϕ , between the wave front and explosive strand may then be determined:

$$\phi = \arcsin\left(\frac{r}{y}\right) = \arcsin\left(\frac{V_D}{V_E}\right) \quad (8)$$

Since the angle is a function only of the respective detonation velocities, which are constants, it too will be a constant.

Explosive strand initiation thus provides a convenient means of orienting the gas detonation shock wave relative to a test surface. The simplest case is shown in Figure 3, where the explosive strand is laid parallel to the test item surface. In this case the angle between the wave front and the test item is the same as the angle between the wave front and explosive strand, and the sweep velocity may be found by combining equations (1) and (8), noting that $\alpha = \beta$ in this particular case:

$$v_S = \frac{v_D}{\sin \alpha} = \frac{v_D}{\sin \beta} = \frac{v_D}{\sin \left(\arcsin \frac{v_D}{v_E} \right)} = v_E \quad (9)$$

That is, for the special case where the initiating explosive strand is parallel to the test surface the sweep velocity is identical to the solid explosive detonation velocity. Actually, this could have been determined by inspection. If the wave angle remains constant as stated previously, then both ends (the point of initiation and the point of contact) must necessarily travel at the same velocity.

Next, let us consider the general case in which the explosive strand is at some angle, ϕ , with the test surface, as shown in Figure 4. The wave front meets the test surface at the angle α . From inspection of the geometry, it is seen that

$$\alpha = \beta - \phi \quad (10)$$

Proceeding as before, combining equations (1), (8), and (10), the general equation for sweep velocity is found as

$$v_S = \frac{v_D}{\sin \alpha} = \frac{v_D}{\sin (\beta - \phi)} = \frac{v_D}{\sin \left(\arcsin \frac{v_D}{v_E} - \phi \right)} \quad (11)$$

The denominator in equation (11), being a sine function, will always have an absolute value between zero and one. Therefore, the sweep velocity will always be equal to or greater than the gas detonation

velocity; i.e., the gas detonation velocity is the lower limit of pressure wave sweep velocity for a test item being loaded by a solid explosive-propagated gas detonation. There is no theoretical upper limit, for as the denominator in equation (11) approaches zero, sweep velocity approaches infinity, the case shown in Figure 2-(b).

It is to be expected that variations in the angle at which the wave strikes the test surface will have an effect upon the pressure exerted on the surface. Two distinct values of peak pressure are associated with a detonation wave in a gas. These are the static pressure and the reflected pressure.⁵ Static pressure, sometimes called overpressure or sidewall pressure, is the pressure exerted on a surface at right angles to the wave front, as in Figure 2-(a). Reflected pressure, also known as total or "head-on" pressure, is the pressure exerted on a surface facing directly into the oncoming wave, as in Figure 2-(b). As one might expect, the reflected pressure is much higher than static pressure because of the kinetic energy delivered by the flowing detonation products. For most explosive gases, reflected pressures are about 2.5 times greater than static pressures.⁶

While considerable information is available from the literature concerning static and reflected pressures in detonations, very little has been said concerning the pressure produced by a wave at oblique

incidence to a solid surface. For a first approximation, an equation was derived based upon the assumption that pressure would be a simple function of the cosine of the angle (α) between the wave front and test surface:

$$P = P_S + (P_R - P_S) \cos \alpha \quad (12)$$

where

P = pressure on test surface

P_S = static detonation pressure

P_R = reflected detonation pressure

α is the same as in Figure 4.

Equation (12) is not an exact relationship, but merely an interpolation of pressures between two known extreme values, those for α equal to zero and to 90 degrees. Another assumption inherent in the foregoing analysis is that the detonating solid explosive strand contributes nothing to the pressure exerted on the test item surface. This condition may not be realized in the actual test setup, and actual pressures are likely to be higher than those predicted by equation (12).

One conclusion which may be drawn from equations (10) and (11) is that the angle α must be relatively small if sweep velocities are to be much above the gas detonation velocity. For small values of

α , equation (12) states that the pressure will be nearly the reflected pressure, P_R . Furthermore, for small angles, the pressures will be relatively unaffected by angle changes which produce considerable variations in sweep velocity. For example, decreasing α from 30 to 15 degrees would nearly double the sweep velocity, but would produce only about eleven percent change in pressure. A test designer would therefore be able to choose different sweep velocities or rise times in a given setup without materially affecting peak pressures and accelerations.

Experimental Equipment and Procedures

A number of tests have been performed to study experimentally the behavior of high explosive initiated gas detonations and to develop practical shock test methods using the forces generated by these detonations. The procedures and equipment common to all tests will be described first, followed by descriptions of each type of setup.

For most tests the explosive gas was the stoichiometric mixture of hydrogen and oxygen, the detonation characteristics of which are listed in Table 1. The hydrogen-oxygen mixture was chosen because the constituent gases are stable, nontoxic, readily available commercially, and relatively low in cost. No special handling procedures are required, other than those required for any flammable gas, and pure water vapor is the only detonation product.

Acetylene-oxygen mixtures were used in several tests. Acetylene mixtures are not generally suitable for the types of tests we are considering because acetylene is unstable at high pressures and produces undesirable detonation products. However, acetylene-oxygen detonations yield approximately twice the pressures of hydrogen-oxygen mixtures under the same initial conditions. In certain instances the pressure advantage might possibly outweigh the disadvantages in other areas. For this reason, data on acetylene detonations were desired to supplement hydrogen-oxygen data.

The gases used in our tests were drawn from commercial cylinders. A simplified schematic of the metering arrangement is shown in Figure 5. The required mixture proportions were obtained by adjusting the gas volume flow rates by means of a needle valve and flowmeter in each line. Check valves were also inserted in each line as a safety measure to prevent detonation pressure or flame from reaching the metering equipment and gas bottles. The flowing gases were mixed at a tee connection near the test fixture. Upstream or metering pressures were always at least twice the maximum test fixture pressure so that flow rates would not change appreciably as the test fixture filled.

Any air initially present in the test fixture had to be removed prior to firing; otherwise, its presence would have degraded detonation pressure and velocity. If the fixture was well sealed, the air was evacuated with a vacuum pump. For unsealed fixtures, the normal

procedure was to flush out the air by passing several volume changes of the explosive mixture through the fixture.

The solid high explosive used was a commercial detonating fuse, known as Primacord, manufactured by the Ensign-Bickford Company. Primacord is a strong flexible cord, made up of plastic tape and textile braid, containing a core of high explosive. The particular core load used in our tests was 25 grains of PETN per foot of cord. Primacord is relatively insensitive to accidental firing from heat, impact, or electrical discharge, it may be handled with ease and safety, and it is available as an off-the-shelf item, at low cost, from most construction or mining supply houses. When properly initiated it detonates at the rate of 21,000 feet per second.¹⁰

The Primacord was initiated by a detonator of the exploding-bridge-wire type, manufactured by Mound Laboratories as the Model SE-1 detonator. This detonator contains 0.25 gram of PETN plus 0.05 gram tetryl booster. The choice of detonator was based upon safety considerations. The SE-1 contains no sensitive primary explosives, and the probability of an accidental firing from heat or static discharge is quite low, much less than that for ordinary blasting caps. The detonators were fired by a special circuit which discharged a 3.5 mfd capacitor at 5000 volts into the detonator bridge wire.

The first tests were performed in frangible wooden chambers such as the one shown in Figure 6. These chambers were 26.5 inches square by 12 to 18 inches deep inside, and were made of 3/4 inch thick fir plywood walls set on a 1-1/2 inch thick plywood base. The tops were of 0.010 inch thick Mylar plastic film supported on an open wooden grid. Five to nine strands of Primacord were strung through the box parallel with the base surface. These strands were gathered together at one end to a single detonator, and all strands were of equal length between the detonator and the box. The explosive gas mixture was introduced through a hose near the base. Three pressure transducers, enclosed in steel slugs for protection, were mounted in the base, flush with the surface.

The wooden chambers were, of course, one-shot setups, with a new chamber required for every test. However, the chambers were convenient for several reasons: (1) they were quickly and easily fabricated; (2) any modifications desired on a particular test could be made on the site by test personnel using only basic hand tools; (3) after the explosion the chamber would remain intact long enough to permit the required measurements to be made, but yet disintegrate before shock wave reflections could be set up which might obscure the data.

The primary purpose of the wooden chamber tests was to investigate the sweep velocities and pressures created by a Primacord-initiated

gas detonation, and, if possible, to confirm the predictions given by equations (11) and (12). Several other parameters were studied also. These included the effects of varying the amount of Primacord, varying the distance between the Primacord and the test surface (base), and changing the composition of the gas mixture.

The information gained from the wooden chamber tests was then used to design and construct a permanent steel chamber and firing table for additional tests. The steel chamber, shown in Figures 7 and 8, is made of standard structural steel channels welded together to form a rectangular chamber. The chamber is bolted to a firing table, consisting of a 5-inch thick slab of steel on a set of legs. Five pressure transducers are mounted in the firing table flush with the surface. Explosive gases are introduced through a pipe fitting in the table. Inside dimensions of the chamber are 36 by 60 inches and the depth is 12 inches. The chamber was designed such that additional sections could be stacked on the present assembly to give greater volumes, although this has not been done on any tests to date.

For a test the chamber is covered by a sheet of plastic film on a wooden frame. This blow-off cover eliminates a potential reflection surface, as well as permitting escape of the detonation products so that excessive pressure forces are not exerted on the chamber walls.

The high explosive strand array was attached to the wood and plastic cover. For different tests the arrays were oriented at different angles with respect to the table surface in order to investigate the validity of equation (11) relating sweep velocity to explosive strand angle.

An interesting design feature of the steel chamber is a perforated liner shown in Figure 8; the purpose of the liner is to damp out shock wave reflections from the walls. This concept has been previously used in hypervelocity shock tunnels and in an explosive gas powered projectile launcher.^{1,11} The liner, consisting of perforated sheet metal, is mounted on standoffs 3 inches from the inside wall surfaces.

Both the wooden and steel chambers were for research into the aspects of high explosive initiated gas detonations, although either could be easily adapted to actual shock testing of small components. However, the relatively small dimensions and volumes of these chambers limited pulse durations to less than a millisecond. In order to produce longer duration pulses tests were performed in two detonation shock tubes. The first shots were fired in a 16-inch diameter, 14-foot long tube. While even a tube of this length will not produce much longer pulses than those obtained in the small chambers, the first tests were performed in it mainly to study the effects of a cylindrical explosive strand array.

The Primacord for a test in the 16-inch tube was strung on a cylindrical wooden frame about 6 feet long, shown in Figure 9, which closely fit the inside diameter of the tube. The test item was a simple aluminum cone about 18 inches long, containing pressure transducers mounted flush with the cone surface. The cone was suspended by wires at one end of the tube and in the center of the Primacord array, as shown in Figure 10. Transducer cables were protected by being enclosed in several feet of hydraulic hose. Plastic covers on the ends of the tube contained the explosive gas mixture until firing. One strand of Primacord was connected from the array to a detonator at the opposite end of the tube from the test item.

Tests in the 16-inch tube were followed by a number of tests in a larger diameter, much longer tube, obtained by converting the Sandia Corporation 26-inch air gun facility to explosive gas operation. The air gun has been in use for several years as a facility for shock testing large items with compressed air supplying the driving force. It consists of two 16-inch naval rifles bored to 26 inches inside diameter and joined end-to-end to form a barrel 90 feet long. The explosive gas conversion consisted of the addition of 40 feet of steel pipe, having an inside diameter of 29 inches, to one end of the gun barrel. The extension formed the test section, containing the test item and all instrumentation. The result, therefore, is a detonation tube 130 feet long, with a total volume of nearly 600 cubic feet.

An instrumented cone, very similar to the one used in the 16-inch tube tests but containing additional transducers, was used as a test item. The cone was rigidly mounted to a transverse strut located inside the test section, 20 feet from the end. Rigid mounting of a test item would not be the normal procedure in an actual mechanical shock test because test specifications usually include an acceleration or velocity change. However, the primary objective of these initial investigations was to evaluate the applied pressure pulse, the characteristics of which are virtually independent of test item motion. Since no motion was required, rigid mounting could be used, thereby reducing the possibility of damage to the test item and instrumentation, and generally improving the amount and quality of data obtained.

Primacord, loaded with 25 grains of explosive per foot of length, was used as the solid explosive in the 130-foot gun tests. For the first few tests the strands were arrayed on cylindrical wooden frames, very similar to those used in the 16-inch tube, shown in Figure 9. Twelve strands of Primacord were equally spaced around the frame, and were tied together to a single strand at one end. When the frame was loaded into the gun, the single strand of Primacord was strung the full length of the barrel to a detonator at the opposite end of the gun from the test item. This arrangement assured that the entire

volume of explosive gas in the gun ahead of the test item was detonated before the Primacord and gas layer surrounding the test item was initiated. The object was to have the solid and gaseous explosives in the vicinity of the test item provide the desired sweep velocity and initial peak pressure. Then the flow of the large volume of detonation products from the gases in the tube ahead of the test item would produce the long duration decay portion of the pulse.

Pressure records from the first few Primacord-initiated shots in the 130-foot gun contained undesirable multiple peaks during the first 2 or 3 milliseconds following the initial peak. These additional peaks were suspected to be the result of transverse shock wave reflections between the test item surface and the gun wall. In an attempt to reduce these reflections, a perforated sheet metal liner was inserted into the 29-inch diameter test section, surrounding the test item. The liner was approximately 26 inches in diameter, leaving a gap of about 1.5 inches between the liner and tube wall. In several tests the Primacord strands were located in this gap, attached to the outside of the liner, and in one test the strands were arrayed on the inside of the liner. The number and spacing of Primacord strands was the same for all tests, with or without the perforated liner. Figure 11 shows one of the liners loaded with Primacord and ready for insertion in the gun.

Since the test item was a cone, and since the explosive strands were always laid parallel to the gun wall, the angle between explosive strands and test surface was simply the cone half-angle. For the particular combination of cone angle, gas mixture, and solid explosive initiation used in the 130-foot gun tests, the anticipated sweep velocity was 30,000 feet per second. The expected pressure normal to the cone surface was 43 atmospheres, assuming no pressure contribution from the Primacord. A pulse duration of 12 milliseconds was predicted, based upon results of previous experiments in smaller tubes.

In all tests the pressures were measured with commercially available piezoelectric transducers. Several makes and models were used. Signals were recorded on magnetic tape and played back at reduced speed into a paper recording oscillograph. The overall frequency response of the system, from transducer to oscillograph recording, was flat within 10 percent from 0 to 40,000 cps and 3 db down at 80,000 cps. Velocities were determined from the times required for the shock front to pass across two or more pressure transducers known distances apart. The output of each transducer triggered a pulse circuit. The pulse circuit outputs were mixed and displayed on a cathode ray oscilloscope screen, from which times were read for velocity computations. Velocity measurements were considered accurate to within 3 percent.

Experimental Results

The results of ten tests performed in the frangible wooden chambers are presented in Table 2. A typical pressure-time record is shown in Figure 12.

The results may be briefly summarized as follows: (1) Both stoichiometric hydrogen-oxygen and equimolar acetylene-oxygen mixtures at atmospheric pressure were detonated without difficulty by Primacord. (2) Sweep velocities were of the order of 20,000 feet per second, agreeing well with the computed value. (3) Peak pressures agreed reasonably well with predicted values for hydrogen-oxygen mixtures, but were 20 to 28 percent lower than predicted values for acetylene-oxygen mixtures. (4) Pressures from the Primacord alone were appreciable, even at standoff distances of as much as 11 inches (Test No. A-3). However, pressures from the Primacord and gas did not appear to be directly additive. In fact, the data suggested that the maximum pressure is determined by either the Primacord or the gas, whichever is higher, and is not the sum of both. (5) Pulse duration varied according to the thickness of the gas layer between the Primacord and measuring surface, and appeared to be independent of the total volume of the chamber. This was an expected result because the only portion of the gas set in motion in the direction

of the test surface would be that portion between the initiating explosive and the test surface.

The tests in the steel chambers were primarily to confirm predicted values of sweep velocity for different explosive strand inclination angles. Results of six shots are given in Table 3. Excellent agreement of computed and measured velocities was obtained. The relatively small disagreement at the larger angles was probably caused by a slight sag in the Primacord strands, since only a limited amount of tension could be applied to the strands without changing their explosive characteristics.

Agreement of computed and measured pressures in Table 3 is only fair. The pressure-time records for the steel chamber tests were practically identical in appearance with those for the wooden chamber tests, shown in Figure 12.

Six Primacord-initiated shots were made in the 16-inch diameter tube, with the conical test item. The explosive gas mixture in all tests was stoichiometric hydrogen-oxygen. The measured shock front sweep velocities on the test item surface were 27,000 to 33,000 feet per second, with an average value of 29,000 feet per second. These values are in good agreement with the computed value of 30,000 feet per second. More important, however, the agreement indicated that the

test method was applicable to three-dimensional test items and explosive strand arrays as well as to flat surfaces as in the chamber tests.

Ten tests were performed in the 130-foot gun facility to evaluate the performance of Primacord-initiated hydrogen-oxygen in a tube designed to produce long pulse durations. Results and pertinent setup data are presented in Table 4. Several tests in the series (Nos. 1, 3, 6 and 8) were control shots made with no solid explosive present in order to study the pressure pulse from the gas detonation alone. The last four shots in the series were made with the cylindrical perforated metal liner in place surrounding the test item (see Figure 11). In Tests Nos. 7 and 9 the Primacord strands were attached to the outside of the liner, so that the liner was between the explosive strands and the test item, while in Test No. 10 the Primacord was on the inside surface of the liner.

The results of the 130-foot gun tests may be summarized as follows:

- (1) Excellent agreement between computed and measured values of sweep velocity was obtained.
- (2) Agreement of computed and measured pressures was only fair. Possible reasons for the discrepancies will be discussed later.
- (3) Pulse durations agreed reasonably well with the predicted value of 12 milliseconds. Pulse durations were difficult to measure accurately because the long gradual decay did not

permit an exact determination of the end of the pulse. (4) Tests with the perforated liner were accompanied by considerably lower pressures on the test item when the Primacord was between the liner and tube wall, compared to pressures in tests without the liner or with the explosive on the inside liner surface.

A typical test item pressure-time record is shown in Figure 13 for a test in the 130-foot gun with no solid explosive present, thereby illustrating the effect of the gas detonation alone. The pulse shape is the classical blast pressure history, consisting of a very fast rise followed by a long exponential decay. Figure 14 is a typical pressure record from a Primacord-initiated explosive gas test, with all other setup conditions the same as for the test producing the record of Figure 13. The peak pressure is considerably higher in the record of Figure 14, which is to be expected because of the different shock front incidence angle. However, several severe peaks and dips are noted in the first few milliseconds of the pulse. These multiple peaks are suspected as being the shock front reflecting back and forth between the test item and tube wall. The intended purpose of the perforated liner was to break up or damp out any reflections, but the liner design used thus far, a simple cylinder concentric with the gun bore, has proven ineffective. Pressure records from tests with the liner, such as the one in Figure 14,

showed only moderate reductions in the multiple peaks when compared to records of tests without the liner. In any case, however, the multiple peaks fade away after about 2 or 3 milliseconds, and the remainder of the pulse very closely resembles that for the simple gas detonation, shown in Figure 13.

Conclusions

The results of the tests have shown that the usefulness of explosive gas loading as a means of mechanical shock testing may be considerably extended by employing solid explosive strands to propagate the gas detonation. Shock front sweep velocities, and hence pressure force or acceleration pulse rise times, may be controlled over a wide range of values by proper orientation of the explosive strands. The method works equally as well on three-dimensional shapes or simple flat surfaces.

Excellent agreement has been obtained between measured sweep velocities and those computed by the equations developed in earlier paragraphs. Agreement of measured and computed pressures has been only approximate, however. Several reasons for the discrepancies have been advanced. First, the equation for pressure was only an interpolation and was not derived from gas dynamics theory. Second,

the transducers may not have had suitable transient response characteristics to follow the initial portion of the pulse. Either overshoot or attenuation could have resulted, depending upon the ratio of the particular pulse rise time to the transducer natural period. Investigations are now underway to develop instrumentation capable of more accurate measurement of blast pressures. Finally, pressures from the solid explosive strands were not negligible and could have caused reading to be higher than predicted. Tests are planned in which smaller strands of explosive, such as extruded PETN, will be used in order to reduce this effect.

Tests are also planned for additional investigation of methods for eliminating the multiple peaks seen in the pressure records of 130-foot gun tests. The problem appears to be one of designing a baffle arrangement which would eliminate shock reflections without altering the desired pulse characteristics. Design and fabrication of various baffle arrangements are now in progress. Use of smaller amounts of solid explosive might possibly help by reducing the intensity of the initial peak, and this too will be studied.

The use of solid explosive initiated gas detonations promises to be a means of obtaining shock pulses difficult to produce by more conventional test procedures. Pulse rise time, duration, and amplitude

may be varied over wide ranges. Test setups may be simple and inexpensive. The explosive strands may be mounted on wooden or wire frames conforming to practically any test item size and shape, and the assembly enclosed in a plastic bag of explosive gas for short duration, low pressure tests, or in a rigid tube or chamber for longer duration or high pressure loadings.

TABLE 1

Detonation Characteristics of the
Stoichiometric Hydrogen-Oxygen Mixture^a

Composition: $2\text{H}_2 + \text{O}_2$ by volume		
Initial Pressure: atmospheric		
Combustion Equation: $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$		
	<u>Theoretical</u>	<u>Observed</u>
Static Pressure (atm.)	18.59	18.6
Reflected Pressure (atm.)	44.18	62.5 peak 33.8 average ^b
Detonation Wave Velocity (fps)	9360	9500

^aFrom Edwards, Williams, and Breeze.

^bFor first 100 microseconds of pulse.

TABLE 2

RESULTS OF EXPLOSIVE TESTS IN FRANGIBLE WOODEN CHAMBERS

Computed Sweep Velocity = 21,500 ft/sec for all tests

Computed Peak Pressure = 93.0 atm. for $C_2H_2+O_2$ mixture= 41.7 atm. for $2H_2+O_2$ mixture

Test No.	Chamber Depth (inches)	Primacord			Gas Mixture	Sweep Velocity (ft/sec)	Peak Pressure ^c (atmospheres)	Pulse Duration ^c (millisec)
		Standoff ^a (inches)	No. of Strands	Spacing ^b (inches)				
A-2	12	11	7	4	$C_2H_2+O_2$	20,000	68.3	0.30
A-3	12	11	7	4	Air	- -	33.3	0.30
A-4	12	11	7	4	$C_2H_2+O_2$	21,400	67.5	0.40
A-5	12	6	9	3	$C_2H_2+O_2$	21,500	75.0	0.19
A-6	12	3	9	3	Air	19,000	75.0	0.08
A-7	12	3	9	3	$C_2H_2+O_2$	20,000	74.2	0.11
A-8	18	17	5	5.5	$C_2H_2+O_2$	20,700	60.8	0.36
A-9	18	17	5	5.5	$2H_2+O_2$	21,500	40.8	0.28
A-11	12	11	7	4	$2H_2+O_2$	20,000	50.8	0.25
A-13	15	9	7	4	$2H_2+O_2$	20,000	46.7	- -

a. Distance between Primacord and test surface.

b. Distance between Primacord strands.

c. Average from three transducers.

TABLE 3

RESULTS OF EXPLOSIVE TESTS IN THE RECTANGULAR STEEL CHAMBER

Gas Mixture: $2H_2 + O_2$

Initiator: 11 strands of 25 gr/ft Primacord, spaced 3 inches apart, entering chamber 12.5 inches above test surface.

Test No.	Primacord Angle ^a (degrees)	Sweep Velocity (ft/sec)		Peak Pressure ^b (atmospheres)	
		Computed	Measured	Computed	Measured
1	0	21,500	21,300	41.7	38.3
2	0	21,500	21,000	41.7	38.3
3	0	21,500	21,500	41.7	30.0
4	5	26,300	26,500	42.5	31.3
5	7.5	29,600	28,800	42.9	45.0
6	10	33,400	31,300	43.2	50.0

a. Angle between Primacord and test surface.

b. Normal to test surface, 12 inches from nearest Primacord strand.

TABLE 4

RESULTS OF EXPLOSIVE TESTS IN THE 130-FOOT GUN FACILITY

Gas Mixture: $2H_2 + O_2$ at atmospheric pressure

Initiator: 12 strands, 25 gr/ft Primacord,
equally spaced on 26 inch dia.
cylindrical frames, 7 to 20 feet
long.

Test No.	Sweep Velocity (ft/sec)		Peak Pressure (atmospheres)		Pulse Duration ^a (m sec)
	Computed	Measured	Computed	Measured ^a	
1 ^b	9,500	8,800	22.4	27.9	- -
2	30,000	33,700	43.0	65.8	- -
3 ^b	9,500	10,300	22.4	22.5	10.0
4	30,000	30,300	43.0	52.5	12.0
5	30,000	33,300	43.0	66.6	11.1
6 ^b	9,500	9,500	22.4	24.4	9.7
7 ^c	30,000	30,500	43.0	39.2	13.6
8 ^{bc}	9,500	9,200	22.4	14.6	13.1
9 ^c	30,000	- -	43.0	34.2	- -
10 ^c	30,000	- -	43.0	67.8	10.5

a. Average from three transducers.

b. Explosive gas only (no Primacord used) in these tests.

c. Perforated liner in place.

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LIST OF FIGURES

- Figure 1. Idealized Blast Wave Rigid Body Acceleration-Time History.
- Figure 2. Examples of a Detonation Wave Intercepting a Test Surface.
- Figure 3. Detonation Wave Initiated by Solid Explosive Strand,
Strand Parallel to Test Surface.
- Figure 4. Detonation Wave Initiated by Solid Explosive Strand,
General Case.
- Figure 5. Schematic Diagram of Gas Metering Equipment.
- Figure 6. Typical Wooden Chamber Explosive Test Setup.
- Figure 7. Rectangular Steel Explosive Test Chamber.
- Figure 8. Interior of Rectangular Steel Explosive Test Chamber.
- Figure 9. Explosive Strand Array for 16-inch Tube Test.

Figure 10. Setup for Test in 16-inch Tube.

Figure 11. Perforated Metal Liner and Explosive Strand Array for 130-foot Gun Test.

Figure 12. Typical Pressure-Time Record of a Test in the Wooden Chambers.

Figure 13. Typical Pressure-Time Record of an Explosive Gas Test in the 130-foot Gun, Solid Explosive Not Used.

Figure 14. Typical Pressure-Time Record of a Solid Explosive Initiated Explosive Gas Test in the 130-foot Gun.

ACCELERATION

TIME

RISE TIME

PULSE DURATION

(a) WAVE PROPAGATING PARALLEL TO TEST SURFACE

(b) WAVE PROPAGATING DIRECTLY INTO TEST SURFACE

(c) GENERAL CASE, WAVE AT OBLIQUE INCIDENCE WITH TEST SURFACE.

α = ANGLE OF INCIDENCE OF GAS DETONATION FRONT
 β = ANGLE BETWEEN DETONATION WAVE FRONT AND EXPLOSIVE STRAND

ϕ - ANGLE OF INCLINATION OF STRAND TO TEST SURFACE

WOOD CHAMBER TEST NO. A-4

GAS: $C_2H_2 + O_2$ AT ATMOSPHERIC PRESSURE

SOLID EXPLOSIVE: 7 STRANDS OF 25 ^{GR}/FT PRIMACORD

26 INCH GUN TEST NO. 8
GAS: $2\text{H}_2 + \text{O}_2$ AT ATMOSPHERIC PRESSURE
SOLID EXPLOSIVE NOT USED.

26-INCH GUN TEST NO. 10
GAS: $2H_2 + O_2$ AT ATMOSPHERIC PRESSURE
SOLID EXPLOSIVE: 25 ^{GR}/FT PRIMACORD,
12 STRANDS ON 26-INCH DIA.
CIRCLE