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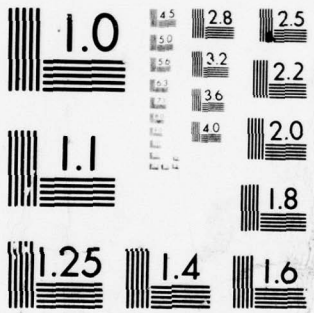

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The propagation rates that occur in loose, granular, confined pyrotechnic compositions were determined for thermal initiation. The same compositions under the same conditions were previously shown to detonate with strong shock initiation. All of the compositions tested developed fast reaction rates which could be extremely hazardous. Burning was found to accelerate to a high rate; this is best explained by a convective burning mechanism. Since the final reaction rates of the loose powder appeared to

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exceed the speed of sound, they are categorized as detonative. Since most rates measured were substantially lower than those observed for strong shock initiation and only slightly higher than the estimated speed of sound, they were considered to be non-ideal, low-order detonations.

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INTRODUCTION

Work was performed to determine the propagation rates in loose, granular confined pyrotechnic compositions when initiated thermally. Previous work by the Hazards Research Corporation (ref. 1) showed that detonations occur when these compositions, under heavy confinement, are shock initiated. The purpose of the work described in this report was to determine whether a detonation would also develop when the compositions were thermally initiated, i.e., burned under the same heavy confinement.

Representative materials included flash, igniter, and flare compositions. The effect of particle size and weight percentages of oxidant and fuel on the reaction rate of one of the flare compositions was also examined. Information gained from these tests will be used to more accurately classify pyrotechnic materials in terms of their potential for damage and the hazards they present in processing, storage, and transportation.

TEST MATERIALS AND TECHNIQUES

Materials

A detailed description of the pyrotechnic compositions tested is given in table 1. The materials consisted basically of four types: igniter (SI-193), flare white (FW-306), photoflash (PFP-555), and flare yellow (FY-1451, FY-1754 through FY-1758) compositions in loose granular form. The particle size and ratio of oxidant-to-fuel were varied for the flare yellow composition to give six different formulations. FY-1451, FY-1755, and FY-1754 were fuel rich. FY-1758, FY-1757, and FY-1756 had stoichiometric proportions of fuel and oxidant. Three different particle sizes of fuel were used: coarse (20/50 mesh), medium (100/200 mesh), and fine (200/325 mesh). The variations were made to determine the effect of particle size and fuel/oxidant ratio on the reaction rate.

Test Fixture

All compositions were tested in the configuration shown in figure 1. The confinement was supplied by schedule 160, ASTM A106 carbon steel pipe (grade B) 121.9 cm (48 in.) long, having an internal diameter of 5.4 cm (2.125 in.) and an outer diameter of 7.3 cm (2.875 in.). Both ends of the pipe were sealed with heavy end caps. This confinement was chosen to duplicate that of the Hazards Research Corporation who found that these materials would detonate when strongly shocked under this

confinement. It was also felt that this confinement gave a sufficiently large charge length-to-diameter (l/d) ratio (approximately 40) and was strong enough to match the conditions that might occur should a large quantity of the powder be ignited in a storage container. A large l/d ratio was necessary because the reaction was expected to start slowly and require a long distance to develop fully.

An igniter pack placed at the bottom of the column was used for thermal ignition. The pack consisted of an antistatic plastic bag containing a standard electric match embedded in 28.4 g (1 oz) of SI-193 igniter. The lead wires were placed against the inside of the pipe and exited through a small hole near the top of the pipe. This arrangement was used because it gave reliable and consistent ignition to all the mixes considered.

Velocity Probes

In the experiments, the propagation rates were measured by using two velocity probes (fig. 2) positioned parallel to the long axis of the charge and supplied by a constant current source (fig. 3). One of the probes had a resistance wire, skip wound with nylon inside a thin aluminum tube, and was called a crush probe (ref. 2) because a relatively high pressure wave will crush the outer tube around the wire causing a change in resistance corresponding to the position of the pressure front. The second probe consisted of two parallel wires, one a resistance wire and the other heavy copper wire, joined at one end. This probe was called an ionization probe because the resistance change is produced by an ionization front shorting the copper wire to the resistance wire. Change in resistance was monitored by a tape recorder. The two different probes were used because it was felt that, if a slow burn occurred, the slow pressure build-up might cause the crush probe to fail erratically while the ion probe would continue to record the slow burn rate. The ionization probe is inherently more noisy than the crush probe, because the path between the two wires is completed by ionization which can have a different resistance depending on the local strength of reaction. If a reaction is pulsating or erratic, each probe reacts in a different way. The crush probe's resistance remains constant if too little pressure is present while the ion probe reacts to too little ionization by a sizable resistance increase. In most cases where one probe fails, the other will continue to give data. When the reaction is sufficiently strong and steady, both probe records are identical.

The two rate probes were bonded with epoxy to a wooden stick 2.5 cm wide by 0.8 cm thick and slightly shorter than the steel pipe (fig. 2). Before loading this rate stick was bonded with epoxy to the inside of the steel pipe (5.4 cm) and the leads passed out through small holes drilled at the top just below the threads. The wooden stick was used for two reasons: (1) for ease in installation, and (2) as mechanical isolation from the pipe wall. In some early tests, the probes were bonded directly to the pipe wall. These tests were characterized by a rapid shorting of the crush probe probably due to a mechanical disturbance in the pipe wall near the top of the probe. This type of probe failure was not observed when the wooden stick was used.

Loading

The pipes, with the rate sticks in place, were loaded by placing the igniter pack at the bottom of the pipe and securing the leads along the inner pipe wall away from the rate stick. The bottom end cap was securely fastened and all lead wire holes sealed with a RTV rubber compound. The pipes, positioned vertically, were filled with composition under vibration to a level approximately 3 cm from the top. The top end cap was secured by hand. The loading density was determined by dividing the weight of the powder in grams by the volume of the pipe.

Testing and Data Reduction

Testing was accomplished directly after loading. The loaded pipe was moved from the loading line to the test area in the vertical position and, still upright, was attached to a heavy fixture behind a fragment barricade. Both probes were connected to their constant current power supplies and the output fed through high impedance voltage dividers (100 K ohms) to an Ampex FR-1300 tape recorder (frequency response of 20 Hz at 60 in./sec). Power to the igniter was supplied by a 12-volt battery and controlled by relays which applied the voltage for approximately 10 milliseconds, then shorted the igniter leads to ground. Four channels of information were recorded: one channel for each of the two probes, the igniter voltage, and a 2 kHz timing signal. The probes, previous to loading, were calibrated in terms of resistance/length. Just prior to firing, a known resistor was momentarily substituted for the probe in the power supply to give an output/length calibration.

After each test the tape recorder was played back at reduced speed and the data recorded on photosensitive paper from a Honeywell Visicorder. All the rates were calculated from the slope of a straight line fitted by hand to the playback traces. For the most part, the rates reported are the maximum measured for the last one-third of the pipe. When the rates were obviously accelerating or noisy, it was difficult to give a single number. In such cases a range of values was quoted.

RESULTS

Two to four tests were performed on each formulation depending on the availability of the powder and reproducibility of the data. The results of all the tests are shown in table 2. A comparison between the shock initiation rates previously obtained (ref. 1) and the average maximum rates obtained in this study are given in table 2. Copies of the actual traces and pictures of the pipe damage are shown in figures 4 through 34.

From tables 2 and 3 as well as the figures, the following observations can be made for the various compositions (see table 1 for composition details):

1. FW-306. The propagation rate was 300 m/sec and the pipes all had the same damage (lead holes enlarged). The rates accelerated to a final steady rate with the maximum rates less than half those for shock initiation.

2. PFP-555. Both tests showed a constant rapid rate immediately after the ignition. However, one rate was almost twice the other. The faster rate produced smaller fragments than the slower rate. The two rates that were measured bracketed the detonation rate for shock initiation so that the average was about the same.

3. SI-193. In most tests a fairly constant rate was recorded. The rates were one-third that of shock initiation. None of the tests resulted in pipe fragmentation.

4. FY-1451. This coarse particle, fuel-rich mixture was very sluggish to ignite. The transition to the rapid reaction took over 50 msec. The final rate (240 m/sec) was much less than that for shock initiation. The pipe fragmented once in four tests, and in that instance the last quarter of the pipe was intact.

5. FY-1755. This formulation with the same fuel-rich proportions as FY-1451, but with a medium particle size, had a fairly rapid transition to the fast rate (10-to-15 msec from application of igniter voltage). The maximum reaction rate (452 m/sec) was constant over the last half of the pipe and in one test was constant for most of the pipe. Three pipes fragmented in four tests.

6. FY-1754. This fuel-rich composition with the finest particle size was quick to develop the fast reaction (less than 10 msec) and had the highest propagation rate of the fuel-rich compositions (627 m/sec). The rate was constant over the last half of the pipe except in test number 1 of the series where it appears to have accelerated along the entire length. Only one pipe fragmented in the three tests.

7. (FY-1758. This composition with coarse particles and stoichiometric proportions of fuel-to-oxidant was sluggish to develop the fast reaction (greater than 50 msec) and showed pulsating or intermittent transitions between a slower and faster rate. The maximum rate (277 m/sec) was slightly higher than its fuel-rich counterpart (FY-1451), but was developed near the end of the pipe (last quarter). All but one pipe fragmented in four tests.

8. FY-1757. This composition with medium particle size and stoichiometric proportions of fuel and oxidant developed a fast reaction in 15 to 20 msec. Very rapid rates approximately equal to shock initiation values for FY-1451 (1046 m/sec) were observed at the end of the pipe (last quarter) in two of the three tests. In one test a relatively smooth transition to a constant rate (534 m/sec) slightly higher than its fuel-rich counterpart (FY-1755) did develop over the last half of the pipe. All pipes fragmented.

9. FY-1756. This fine-particle stoichiometric composition was quick to develop a fast reaction (10 to 15 m/sec) which achieved approximately the same high rate as the medium particle composition (FY-1757) over the last third of the pipe by a smooth acceleration. In the two tests, both pipes fragmented.

DISCUSSION

The purpose of this work was to determine whether a deflagration-to-detonation transition could be initiated in formulations in which it had previously been demonstrated that a strong shock would cause detonation (ref. 1). The results in table 3 show that only PFP-555 and the stoichiometric fine- and medium-particle variations of FY-1451 (namely FY-1756 and FY-1757) develop rates equal to those for strong shock initiation, while the maximum rates measured for the other formulations are substantially lower.

Even though low rates were measured for many of the compositions, these rates are much faster than normal burning rates and do produce explosions.

Definitions

The results of this work are to be used in a revision of the Army Technical Bulletin TB 700-2, "Explosives Hazard Classification Procedures" (ref. 3). Appendix B of the current edition includes the following definitions:

A deflagration is "a rapid chemical reaction in which the output of heat is sufficient to enable the reaction to proceed and be accelerated without input of heat from another souce. Deflagration is a surface phenomenon with the reaction products flowing away from the unreacted material along the surface. Confinement increases pressure, rate of reaction, and temperature. The final effect of deflagration under confinement is explosion."

A detonation is "a violent chemical reaction within a chemical compound or mechanical mixture evolving heat and high pressures. A detonation, in contradistinction to deflagration, is the reaction which proceeds through the reacted material toward the unreacted material at a high constant velocity. The velocity of the reaction is supersonic. The result of the chemical reaction is exertion of extremely high pressures on the surrounding medium forming a pressure wave (blast wave) which propagates away from the source at supersonic velocities. A detonation when the material is located on or near the surface of the ground is normally characterized by a crater."

Brown and Collins (ref. 4) give technically more exact definitions: "Deflagrations are burning phenomena whose propagation rates are controlled by transport processes and by chemical kinetics. They are characterized by the dependence of the linear burning rate of the ambient pressure, and their reaction rates are low compared to those of detonation. In the condensed phase, propagation rates in void-free materials range from a fraction of a centimeter per second to about 12 centimeters per second at 1000 psi. Laminar burning in gases at one atmosphere ranges from 3 cm/sec for propane-air to about 75 cm/sec for hydrogen-air. In turbulent gases the rates may reach hundreds of meters per second.

"In the unconfined state, the pressures generated by deflagrations are low, and on the order of inches of water. If the material is confined, as in a gun, the pressure is essentially that given by the gas law for the appropriate adiabatic heating and increase in the number of moles of gas.

"Detonations are reactive wave phenomena whose propagation is controlled by shock waves. Theoretical analyses assume that reaction rates are essentially infinite and that chemical equilibrium is attained. Therefore, the actual propagation rate is considered to be governed solely by thermodynamics and hydrodynamics. The propagation rates of detonations are orders of magnitude higher than those of deflatration, i.e., thousands of meters per second.

"The pressure generated in detonations is very high, whether confined or unconfined, due to the very high propagation rate. The gases have not had time for expansion; a pressure pulse can oly move at sonic velocity, and the detonation front moves at supersonic velocity."

The different definitions are stated here to point out that the difference between deflagration and detonation is more than just a supersonic propagation rate: it also involves the mechanism producing the reaction.

There are phenomena that have different characteristics from the conventional deflagration and detonation described above. These are:

(1) Ideal detonation in low-density media.

(2) Non-ideal detonation.

(3) Low-velocity detonation (LVD) in liquids and solids.

(4) Convective deflagration.

"Ideal" means that the detonation processes are determined by only two independent parameters, the initial chemical composition and the loading density of the explosive material. Reaction rates and geometric factors are not considered in calculating infinite diameter detonation velocity. For finite dimensions and real confinements, detonation velocities are altered slightly. Shock initiation above a critical level leads to the same detonation properties in each case.

"Non-ideal" detonations are generally associated with a finite rate of release of energy which does not achieve full release within a steady state reaction zone length. For a given explosive composition and physical state, there is a critical diameter, d_c, below which wave propagation fails and a diameter, d*, above which the detonation velocity attains its maximum theoretical value. Detonations propagating in charges having diameters between d_c and d* are termed "non-ideal". Both d_c and d* are affected by particle size and confinement. For a given diameter, the detonation velocity is dependent on confinement. These "non-ideal" detonations have reproducible velocities independent of shock level above a critical shock strength, but are lower than those calculated simply on the basis of chemical composition and loading density. Examples are AMATOL, AMATEX, and MINOL.

The reactions observed here, with the possible exception of those formulations with the same velocity as those initiated by strong shock (ref. 1) are neither ideal nor non-ideal detonations because, under the same initial conditions, different rates were observed for different initiation and the velocities were not reproducible.

The term "low-velocity detonation (LVD)" is applied to a reaction that propagates in an explosive at about the sonic velocity for the unreacted material. It is a special case of coupling between a shock and a reactive region behind. In the same energetic material under different initiation or geometrical configurations, a "normal" or high-velocity detonation (HVD) may also occur. Both HVD and LVD propagate as steady-state reaction wave phenomena, but transitions from LVD to HVD and from LVD to failure are also observed.

Convective deflagration or burning (CB) is an ultra-fast burning produced by the forced convection of hot reaction products into the unreacted material by high pressure which is produced from a lesser reaction under confinement. Convective burning is usually a transient step between

deflagration in loose granular media and the onset of detonation. It is possible that LVD is an intermediate or final phase of this transition.

Deflagration Detonation Transition (DDT)

The transition from burning to detonation or one of the intermediate phenomena mentioned above is called deflagration detonation transition (DDT). Many have investigated DDT in high explosives (ref. 5-10), and a good survey of the work in this area prior to 1967 can also be found in reference 4.

According to reference 8, the basic requirements for DDT are:

(1) The energetic material must burn rapidly enough for a high equilibrium pressure to be reached (and reached rapidly) in the confined burning region, despite heat losses to the surroundings, and

(2) The unburnt energetic material beyond the burning region must be sufficiently sensitive to be initiated by shocks of an amplitude equal to the high burning pressure.

Griffiths and Groocock (ref. 6) investigated the mechanism by which heavily confined columns of solid granular explosives, e.g., RDX, HMX, PETN, and tetryl, burn to detonation. The results showed three stages in the transition process:

(1) A combustion wave, in which the mechanism of heat transfer is conduction, having a propagation rate less than 1 cm/sec.

(2) A combustion wave, in which the mechanism of heat transfer is convection, having a propagation rate up to 2000 cm/sec.

(3) Formation of a shock wave from coalescence of compression waves, and initiation of the detonation reaction.

The second, or convective, stage of the transition is the most important, and is dependent upon three parameters: (1) the temperature of the gas products, (2) the ability of the gases to penetrate the explosive, and (3) the energy transfer rates between the gaseous products and the unreacted explosive.

The convective burning model provides a mechanism for the pressure to build to the point where a shock wave can be formed which is capable of initiating detonation. With porous materials, it is possible to stabilize the high convective burning rates short of a detonation by meeting certain conditions (ref. 10) including:

(1) porosity and permeability of the charge less than certain threshold values,

(2) the maximum pressure in the combustion zone and that in the combustion products maintained constant,

(3) a subsonic flow of the combustion products.

Bernecher and Price (ref. 9) showed that DDT can be induced by the insertion of a gas loader in the initiation system for explosives not capable of the transition by themselves. In their experimental arrangement, Bernecher and Price found that certain porous, granular explosives such as Explosive D, TNT, TNB usually showed the propagation of a convective flame front but no transition to detonation. Evidently this is because the pressure build-up was not rapid enough. To provide a more rapid build-up, a variable length column of a more rapidly burning material was placed between the igniter and charge. This column was called the "gas loader column." When non-detonating 94/6 RDX was used as a gas loader, a sufficiently rapid pressure build-up was achieved to permit a transition detonation. Certain critical lengths of gas loader were found, above which the explosive made a transition to detonation and below which no transition occurred. A relationship between gas-loader length and length-to-detonation was also found. The mechanism producing the detonation was described as a post-convective pressure wave generated in the burning region traveling at the sonic velocity that overtakes the convective flame front and causes detonation shortly thereafter.

Sulimov et al (ref. 10) investigated the conditions under which CB (convective burning) and LVD could be stabilized for PETN. The quasi-steady CB and LVD modes were not experimentally observed over the whole range of possible propagation velocities. For PETN, CB was in the 1-to-10 m/sec range and LVD was 1000-to-3000 m/sec. They postulated certain critical pressures for onset of CB, LVD, and HVD. The values of these critical pressures were dependent on the nature of the explosive, structure (gas permeability, porosity, and grain size), charge diameter, and confinement. In the region of pressures between onset of CB and LVD

conditions exist under which only accelerating CB can occur. The accelerating CB produces a non-elastic compression wave in the unreacted explosive that affects the CB process so that a transition to LVD occurs. The propagation rate of the LVD is dependent on the strength of confinement (higher compression wave); the stronger the confinement, the higher the velocity. The compression wave, for lower pressures, may consist of two parts: an elastic (acoustic) precursor and slower non-elastic part. LVD propagates at a supersonic speed with respect to the two-phase medium behind the elastic precursor; consequently, it is called a detonation phenomenon. Lateral expansion of the confinement wall also provides some of the energy losses that prevent transition to HVD and stabilizes the process in the LVD mode.

Reference 10 states that "CB and LVD differ from normal burning and normal detonations in that only a small part of the total energy is released in the vicinity of the front (10-20%). The rest of the energy is released in an extended burn-up zone due to surface burning of the grains or cavities formed in the explosive and ignited at the first stage."

Comparison of Experiments and Theory

The rate records from the tests (see table 3 and figures 4 through 34) performed during this study show signs of a transition to LVD. Most start with a rate much less than 100 m/sec, then accelerate to a final steady rate greater than 300 m/sec. The transition to the final rate is sometimes abrupt, possible evidence of the presence of the post convective wave described in the literature (ref. 9).

The time (or length) to effect the transition is controlled by the temperature of the products, the ability to penetrate, the porosity, and other factors. A stoichiometric mix, balanced oxidant to fuel ratio, will generally burn hotter than a fuel-rich mix as long as transport phenomena do not control burning. Larger particles may produce a more porous mix, but the large metal particles also supply a good heat sink to cool the penetrating products. Therefore, as is observed, the finer particles with more surface area burn faster, and stoichiometric mixes develop higher pressures more quickly and reach a detonation state more easily.

A simple calculation of the pressure necessary to cause the pipe to fail in hoop-stress yields about 207 MPa (30,000 psi) based on steel of ASTM A7, ultimate strength 414 MPa to 496 MPa (60,000 to 72,000 psi). For PETN, Sulimov (ref. 10) measured the critical pressure (207 to 310 MPa)

for the onset of LVD indirectly in special experiments by making the bursting pressure of his confinement approximately equal to the critical pressure. In all probability the bursting pressure of the confinement used in this work is also in the proper range for the onset of LVD. However, more experiments should be performed to determine the pressure/rate relationship for LVD transition in these particular compositions.

Hershkowitz (ref. 11) while working with a confined mixture of potassium perchlorate/aluminum (15 micron) which was initiated with an explosive at one end, found experimentally that the reaction propagated stably at either a low speed (300 m/sec) with a short reaction zone (2 cm) or a high speed (900 m/sec) with an elongated structured reaction zone (8 cm), with an occasional rapid transition between them. A calculation of the penetration depth from the front into the mixture for diffusion of molecules, thermal energy, and radiant energy showed that these mechanisms have negligible effect at the rates he observed and suggested that a deflagration would proceed at less than 0.3 m/sec. A calculation of the deflagration branch of the Hugoniot by a parametric technique also showed that only deflagration rates of the order of 0.1 m/sec could exist.

Since no data were available on the speed of sound in the potassium perchlorate/aluminum powder, Hershkowitz calculated the speed of sound based on the compression of aluminum powder only. The calculations yielded 37.1 m/sec at 1.40 g/cm^3 rising to 206 m/sec at 1.50 g/cm^3. From 1.50 to 2.35 g/cm^3, the speed rose gradually to 513 m/sec with respect to density. For his loading density of 1.5 g/cm^3, the speed of sound was less than 300 m/sec even if a precompression shock (145 atmos) raised the density. The rates he observed were supersonic and classed as detonations. The compositions tested here have essentially the same mechanical properties as those above, i.e., they are loose granular powders. Therefore, the same reasoning to the speed of sound should apply. The sound speeds were in the same low range as the powder considered by Hershkowitz because of the granular nature rather than the individual speed of sound of the constituents considered alone. Since the compositions tested here are loose granular mixes, and since there is not much difference in the speed of sound of aluminum, magnesium, potassium perchlorate, etc., it is reasonable to assume, within a few percentage points, that all the various powders considered have the same sound-speed relationship as the aluminum powder.

Accepting the same sound-speed values as those derived in reference 11, all the mixes here have a sound-speed less than 300 m/sec, even if compressed considerably. So it seems that the final rates here are supersonic and should be classed as detonations or, more properly, low-velocity detonations.

Hazards of LVD

The difference between a conventional deflagration and conventional high velocity detonation (HVD) is quite striking--a rate several hundred times faster providing greater brisance with concomitant fragmentation, strong blast, and potentially leading to more severe damage. Often the presence of a clean hole in a witness plate is all that is required to determine when an HVD occurs (e.g., in TB 700-2, ref. 3). If an LVD occurs, the damage to witness plates is slight compared to the usual high-velocity detonation (ref. 12).

It was pointed out earlier that in LVD, only a fraction (10-20%) of the energy is released in the vicinity of the front, the rest being released in an extended burn-up zone. This produces the effect of a rather low-pressure but long-duration pulse acting on witness plates or producing blast. The result is that confinement vessels burst into large pieces in the manner of a pressure vessel failure and the blast has a low peak pressure but a long duration. However, the resultant stresses from such loads can lead to great structural damage.

If the blast output of an LVD were to be set equal to the output from the HVD of a conventional explosive (TNT), the same effect would be observed as that which Fletcher (ref. 13) reported with liquid propellant explosions. He characterized the explosions as low-order detonations, followed almost instantly by deflagration.

The blast output/weight of explosives are compared by equating the output to that produced by a certain equivalent weight of TNT. The output may be compared based on either peak overpressure or impulse, the area under the pressure-time curve, at a given location. Fletcher, relating the propellant explosion to an equivalent weight of TNT, found that, based on impulse, a higher equivalent weight of TNT (1.5 factor) was required close in than far away. Based on peak pressure, the equivalent weight was much less (1/4 factor) close in than far away. Although the airshock peak pressure was low, the impulse was fairly high, and large impulse causes extensive damage to structures.

CONCLUSIONS

All of the compositions tested develop fast reactions which could cause explosions and be extremely hazardous. Burning accelerates to a high rate and is best explained as a convective burning mechanism. The final rates appear to be in excess of the speed of sound of the loose powder (ref. 1). The reactions are therefore all classed as detonative. Since the rates are substantially less than those for strong shock initiation (except PFP-555), and only slightly higher than the estimated speed of sound, they are considered to be low-velocity detonations. Of the four basic compositions tested, PFP-555 can develop either a low-velocity or a high-velocity detonation when thermally ignited. The propagation of the mixes SI-193 and FW-306 develops into low-velocity detonations which are considerably slower than the high-order rates developed from shock initiation.

The magnesium/sodium nitrate composition react at rates that vary from slow, low-velocity detonations to high-velocity rates from explosive shock excitation as the particle size becomes smaller and the proportions of mix change from a large fuel-to-oxidant ratio (fuel-rich) to stoichiometric.

Based on comparison with the deflagration-to-detonation of high explosives, it appears that if the powders were more heavily confined or the charge size were larger, the pressure could become high enough to develop into a high-order detonation. This is especially true of powders with the larger particle size. However, given the present size and confinement, the rates produced (unlike those normally produced by high explosives) are too slow to create enough pressure in the detonation zone to cause the pipes to fail. When the pipes do fail, it seems to be characteristic of a pressure-vessel type failure.

More detailed tests are required to characterize these reactions with more certainty. The speed of sound should be determined experimentally and the details of the reaction front should be examined in more detail.

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Table 1. Pyrotechnic compositions tested

Composition	Formulation	Particle size [microns (mesh)]	Weight (%)	Approx loading density (g/m^3)
SI-193	Boron, amorphous	1	24.7	0.81
	Potassium nitrate	25	74.3	
	VAAR		1.0	
FW-306	Magnesium, atomized	(200/325)	52.7	0.79
	Teflon		44.8	
	Nitrocellulose (12.6% N_2)		2.5	
PFP-555	Aluminum	15	40.0	1.75
	Barium nitrate	140	30.0	
	Potassium perchlorate	20	30.0	
FY-1451	Magnesium, atomized	(20/50)	46.0[a]	0.91
	Sodium nitrate	35	45.0	
	Laminac 4116		9.0	
FY-1755	Magnesium, atomized	(100/200)	46.0[a]	0.86
	Sodium nitrate	35	45.0	
	Laminac 4116		9.0	
FY-1754	Magnesium, atomized	(200/325)	46.0[a]	0.76
	Sodium nitrate	35	45.0	
	Laminac 4116		9.0	
FY-1758	Magnesium, atomized	(20/50)	38.0[b]	0.93
	Sodium nitrate	35	56.0	
	Laminac 4116		9.0	
FY-1757	Magnesium, atomized	(100/200)	38.0[b]	0.86
	Sodium nitrate	35	56.0	
	Laminac 4116		9.0	
FY-1756	Magnesium, atomized	(200/325)	38.0[b]	0.76
	Sodium nitrate	35	56.0	
	Laminac 4116		9.0	

[a] Fuel rich.

[b] Approximates stoichiometric proportions for fuel and oxidant.

Table 2. Test results

Composition and weight (g)	Test no.	Crush velocity (m/sec)	Ion velocity (m/sec)	Comments
PFP-555				
4900	1	920	974	Constant rate; pipe in twisted chunks.
4500	2	546	536	Constant rate; pipe in long pieces.
SI-193				
2250	1		278-1266	Noisy accelerating rate; end caps blown off pipe.
2240	2	628	561	End caps blown off pipe only.
2400	3	674	729	Constant rate near end; caps blown off.
FW-306				
2210	1		264	Lead holes eroded; otherwise, pipe intact.
2210	2	328	292	Noisy ion trace; lead holes eroded.
2375	3	300	332	Noisy ion trace; lead holes eroded.
FY-1451				
2520	1			Trace too noisy to measure, takes > 50 m/sec for reaction to develop. End caps off.
2560	2	158	162	End caps off; > 50 m/sec buildup.
2700	3	251	263	Last quarter of pipe intact; the rest blown apart; > 50 m/sec buildup.
2750	4	205	293	End caps off; > 50 m/sec buildup.
FY-1754				
2120	1		717	Acoelerating rate; end caps off.
2200	2	597	549	Accelerates to constate rates; end caps off.
2250	3	637	637	Constant rate over last half of pipe; pipe blown apart.

Table 2. (Continued)

Composition and weight (g)	Test no.	Crush velocity (m/sec)	Ion velocity (m/sec)	Comments
FY-1755				
2400	1	668	323	Pipe blown apart.
2210	2			End caps blown off pipe.
2275	3	455	519	Constant rate over entire length; pipe blown apart.
2250	4	333	414	Pipe blown apart.
FY-1756				
2120	1	999	1080	Accelerating rate; pipe blown apart.
2180	2	1103	780	Accelerating rate; pipe blown apart.
FY-1757				
2400	1		1024	Noisy trace; pipe blown apart.
2380	2	526	542	Pipe blown apart.
2270	3	296-1165	274-1446	Pipe blown apart; high rate over last foot.
FY-1758				
2600	1		336	Noisy trace; pipe blown apart.
2600	2	261	212	Pipe blown apart.
2640	3	194	255	End caps off only.
2680	4	285	398	Accelerating trace; pipe blown apart.

Table 3. Comparison of shock initiation rates with thermal ignition rates

Composition	Shock initiation rate* (m/sec)	Thermal ignition max rate (m/sec)	Relative fuel particle size
SI-193	1786	648	Fine
FW-306	695	303	Fine
PFP-555	736	744	Fine
FY-1451	1046	253	Coarse
FY-1754		627	Fine
FY-1755		452	Medium
FY-1756		991	Fine
FY-1757		940	Medium
FY-1758		277	Coarse

*In accordance with PATM 2146 (ref. 1).

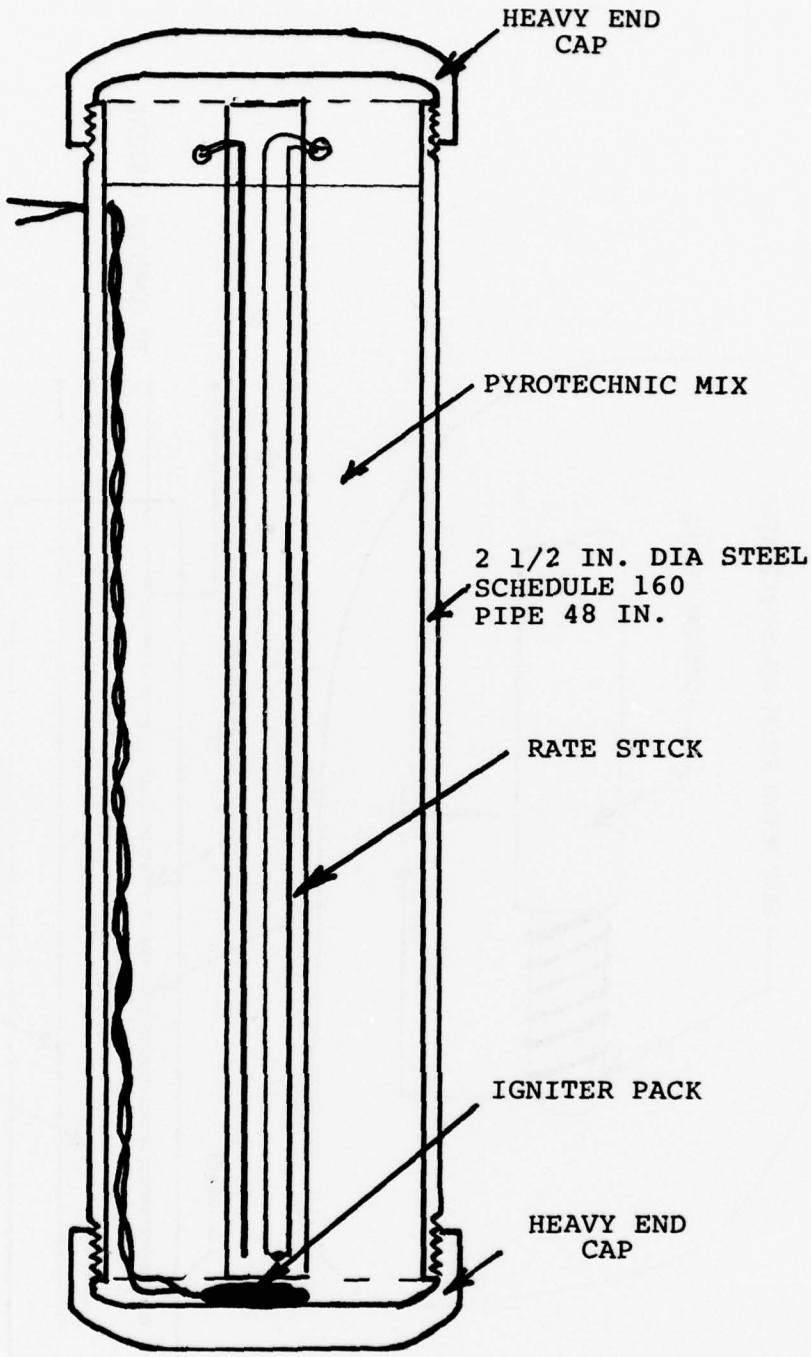


Figure 1. Loaded pipe ready for testing.

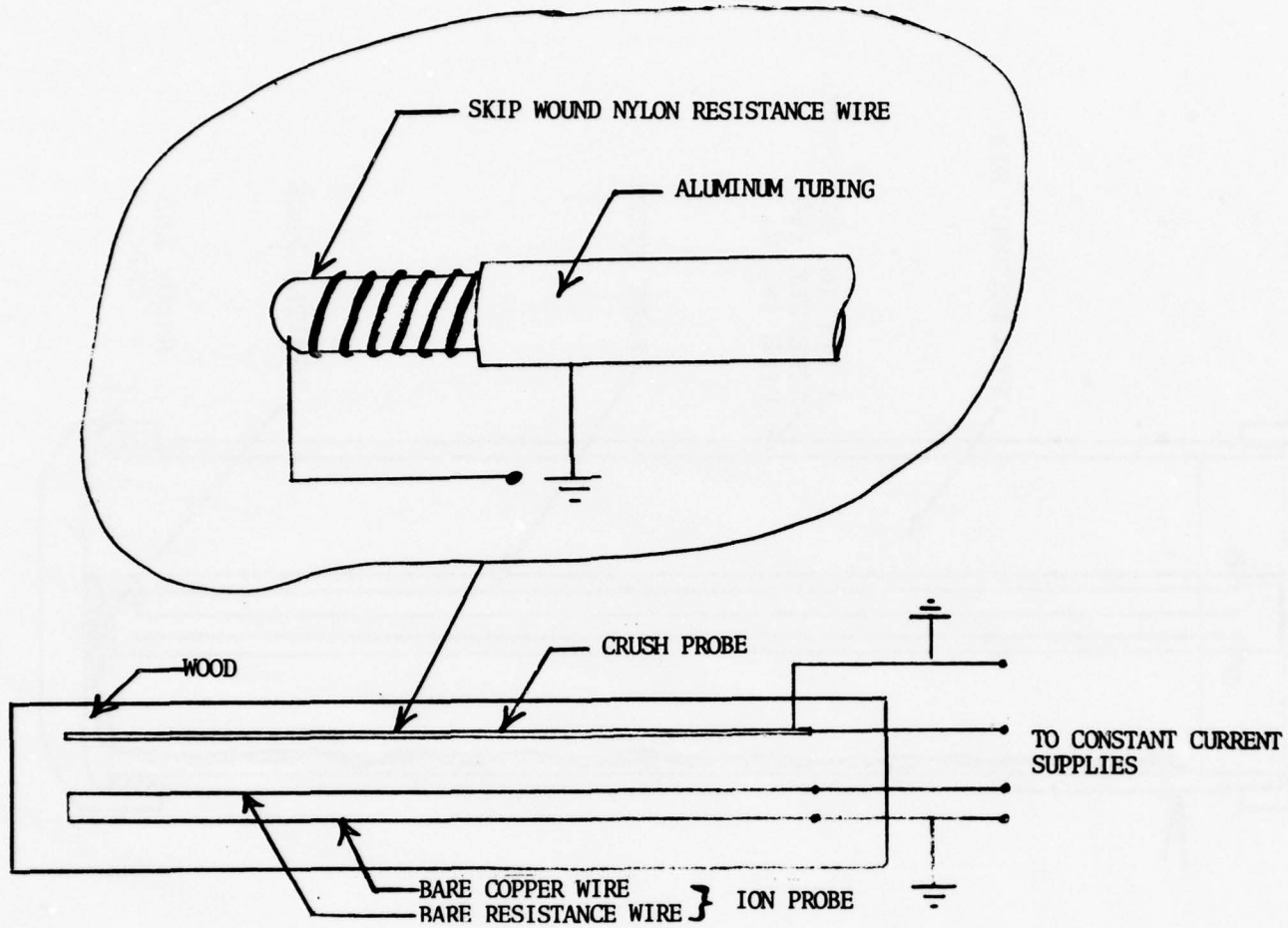


Figure 2. Rate stick showing the crush and ion probes.

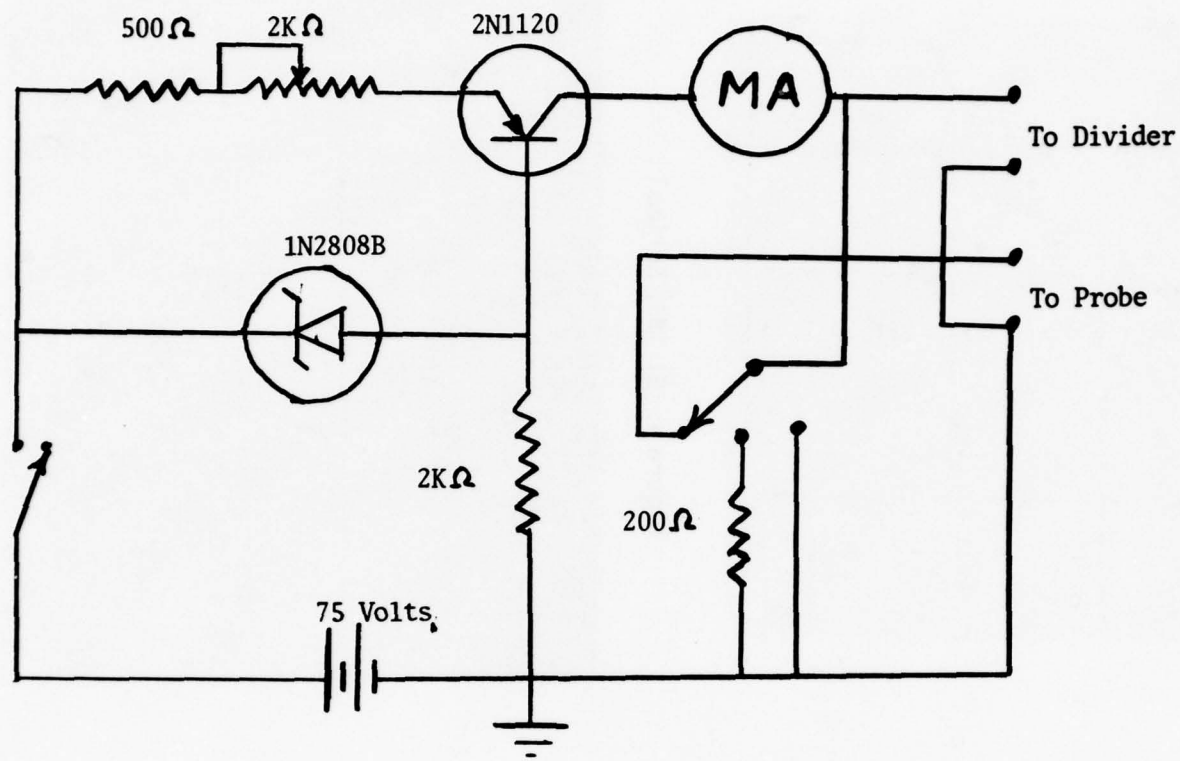


Figure 3. Constant current supply.

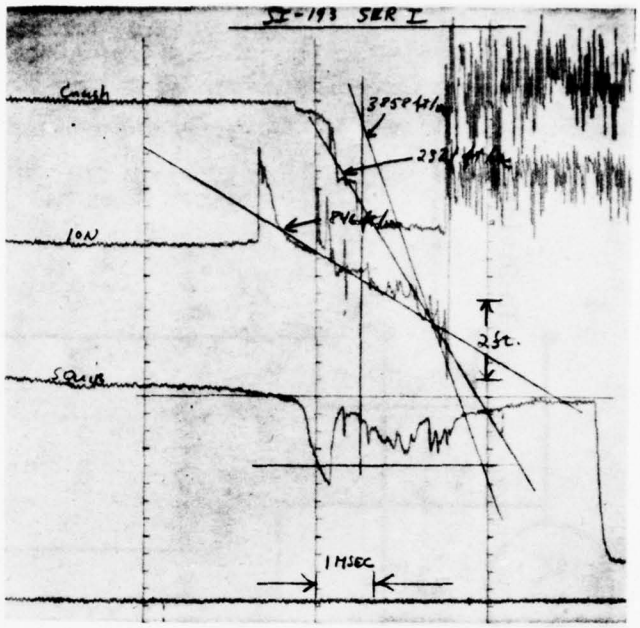


Figure 4. SI-193, Series I .

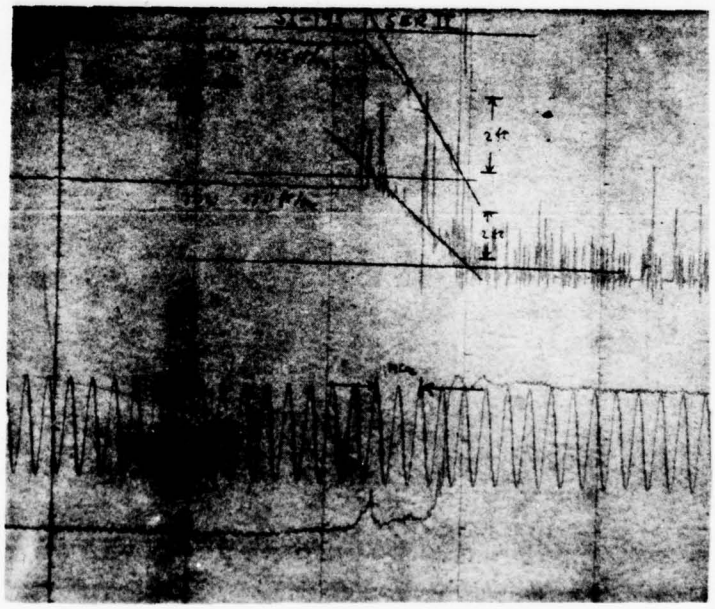


Figure 5. SI-193, Series II .

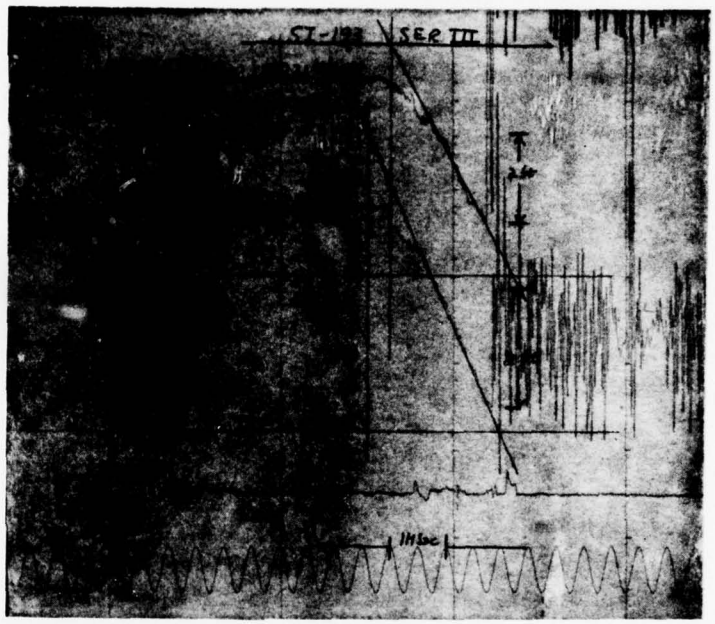


Figure 6. SI-193, Series III.

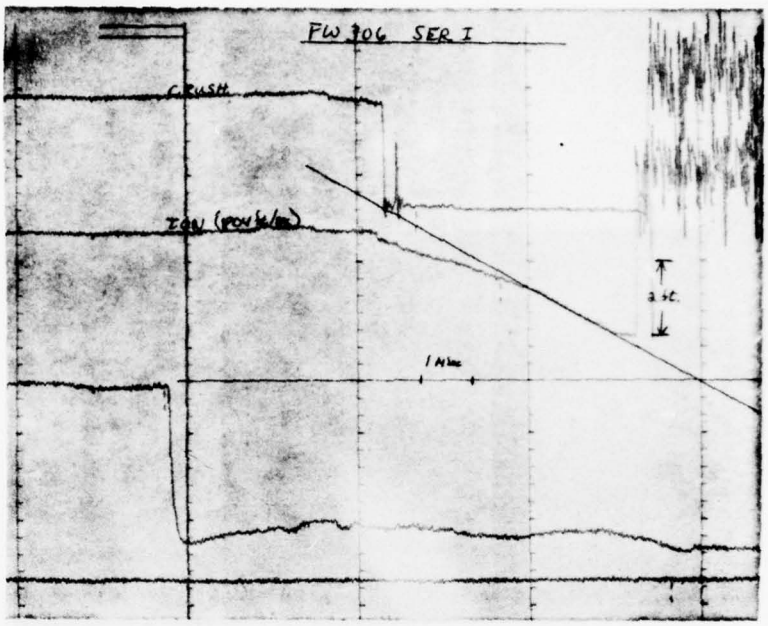


Figure 7. FW-306, Series I.

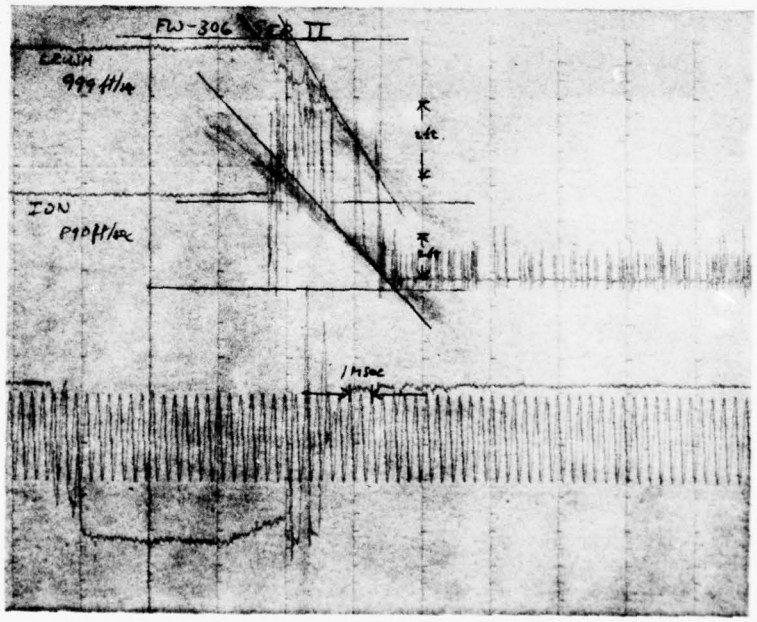


Figure 8. FW-306, Series II.

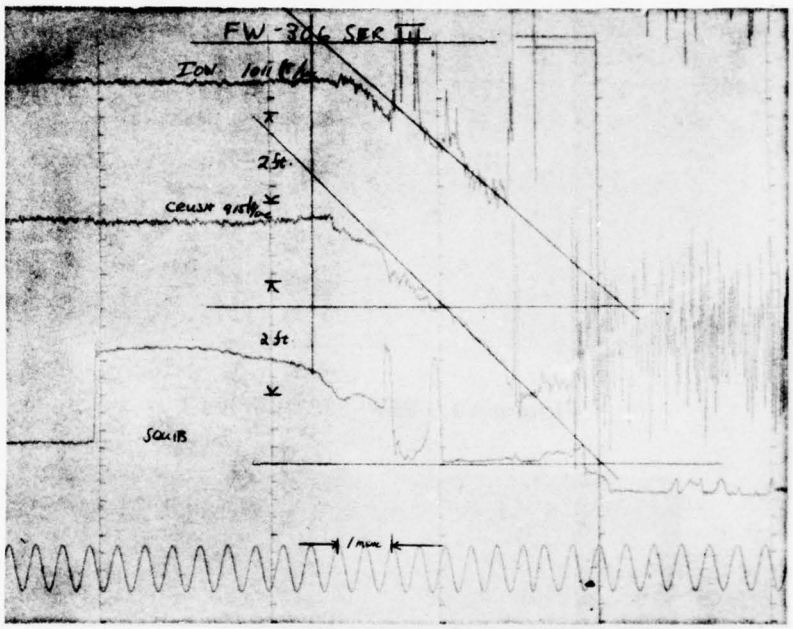


Figure 9. FW-306, Series III.

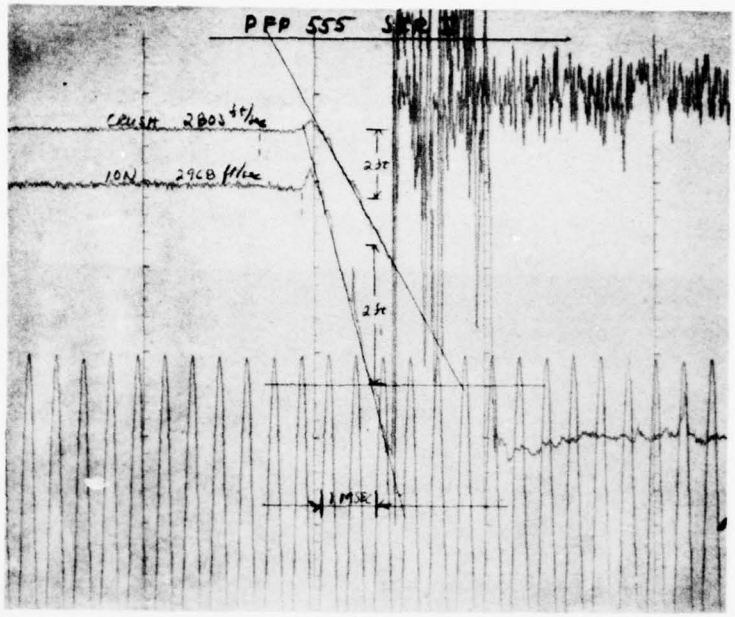


Figure 10. PFP-555, Series I .

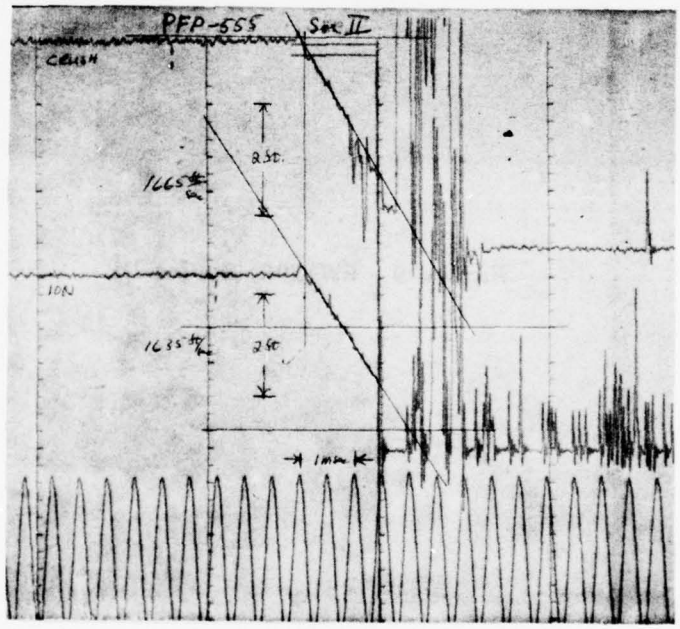


Figure 11. PFP-555, Series II .

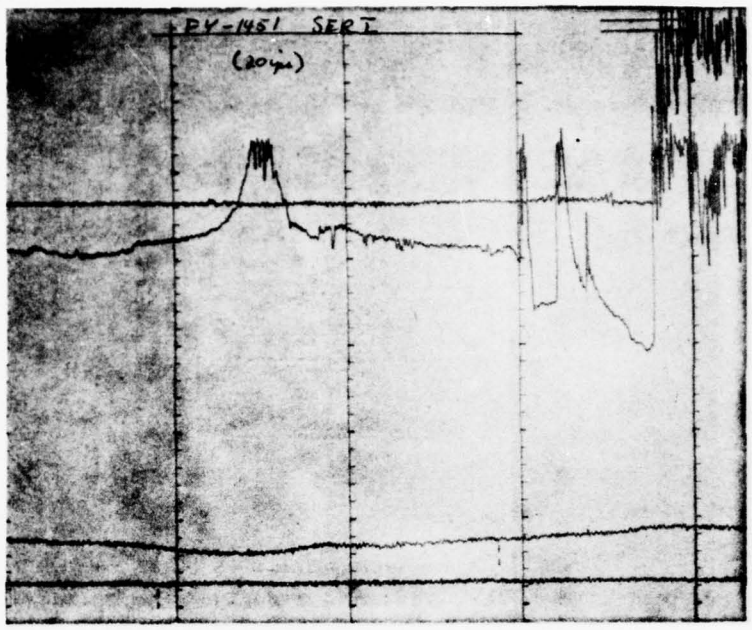


Figure 12. FY-1451, Series I.

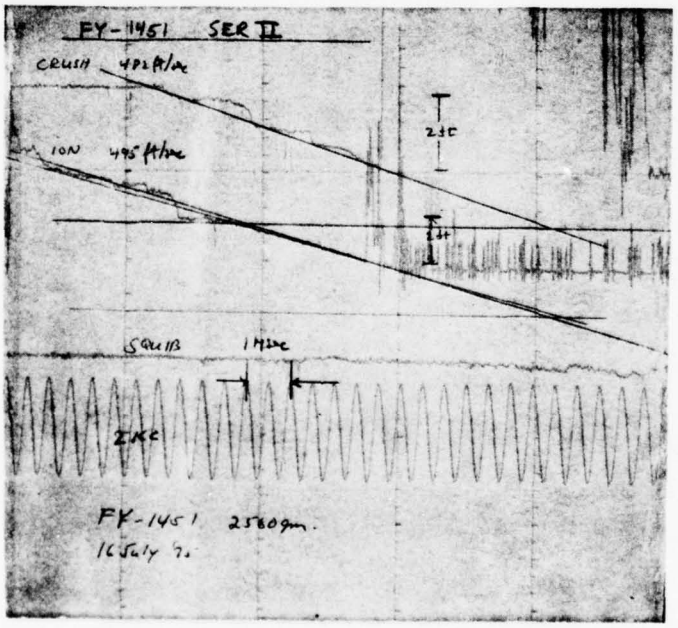


Figure 13. FY-1451, Series II.

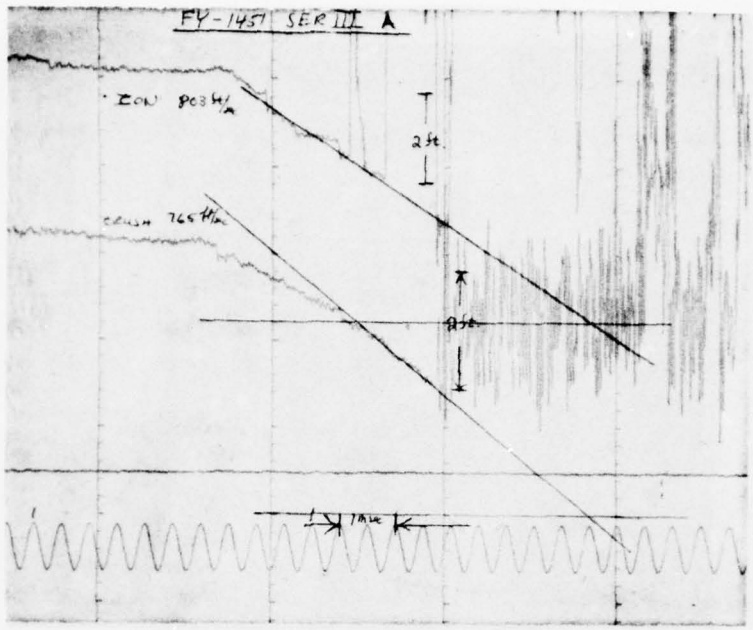


Figure 14. FY-1451, Series III A.

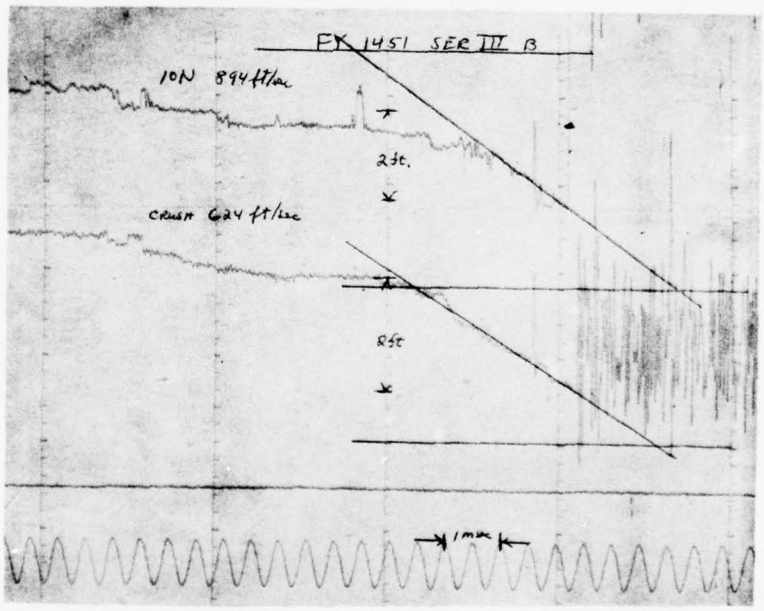


Figure 15. FY-1451, Series III B.

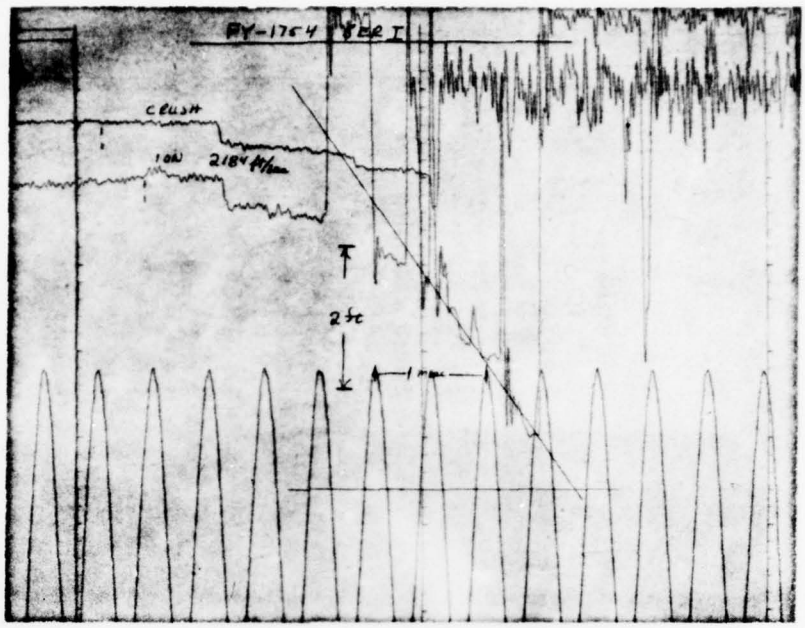


Figure 16. FY-1754, Series I .

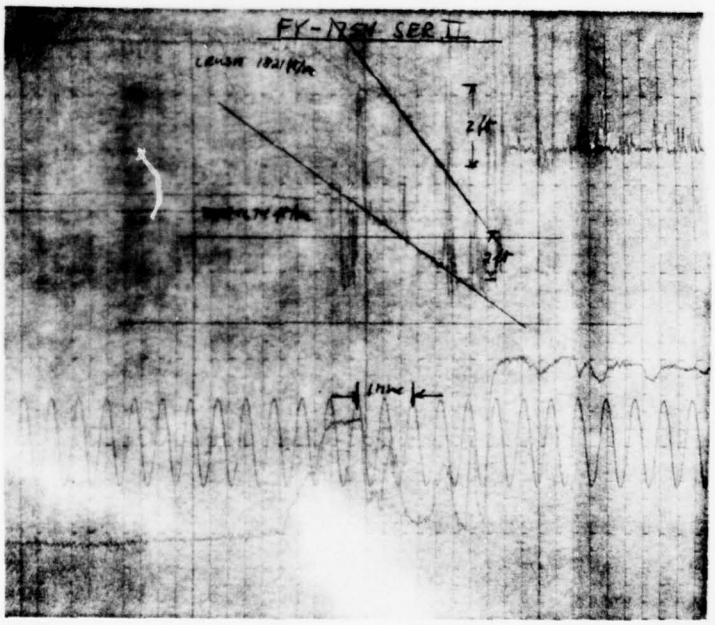


Figure 17. FY-1754, Series II .

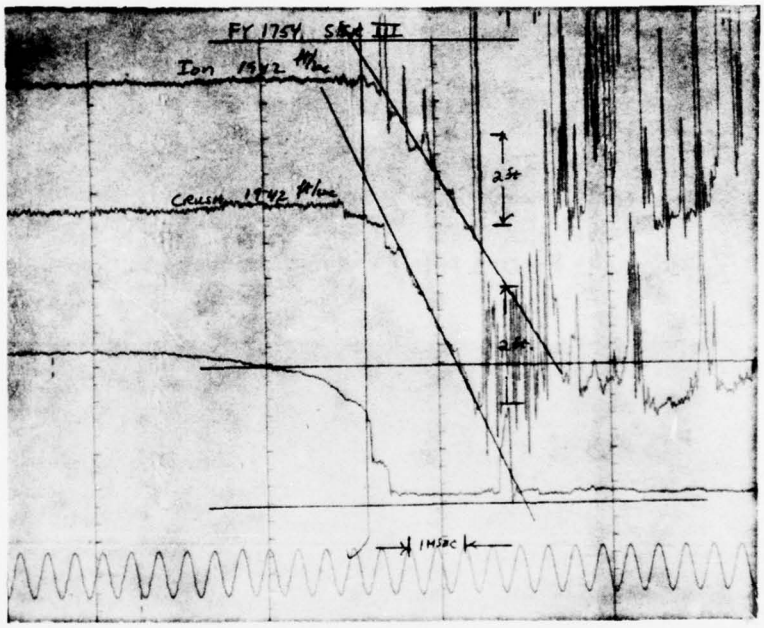


Figure 18. FY-1754, Series III.

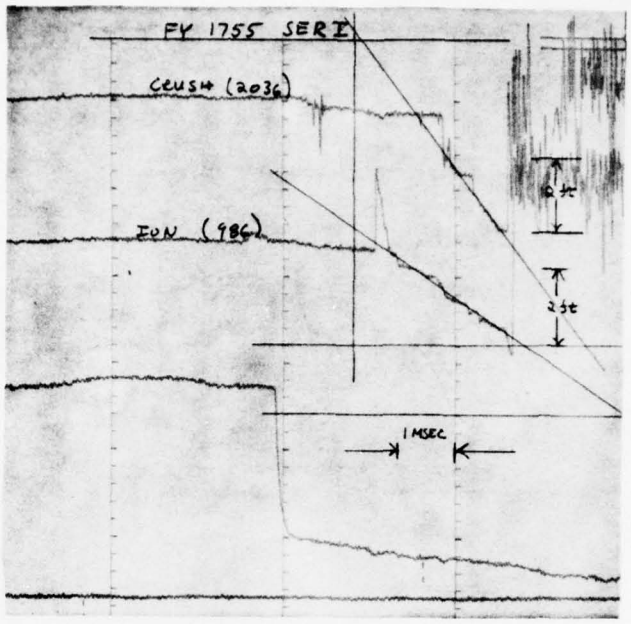


Figure 19. FY-1755, Series I .

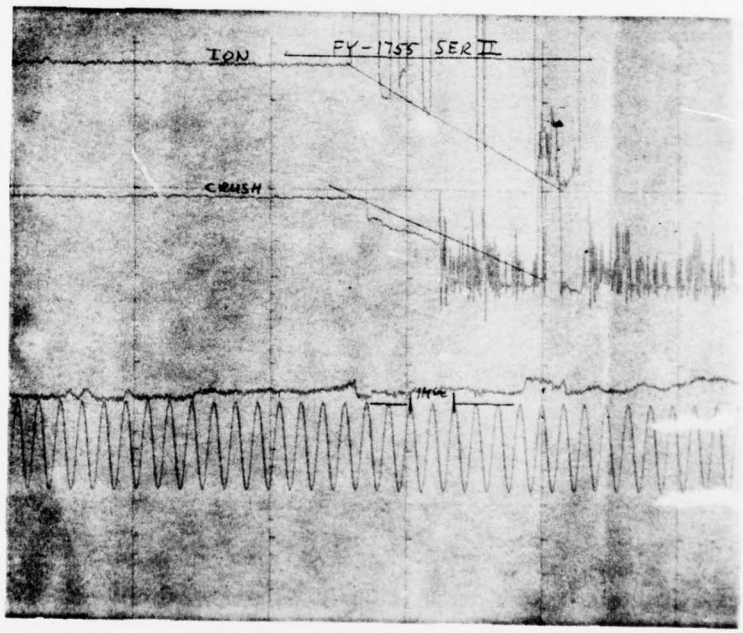


Figure 20. FY-1755, Series II .

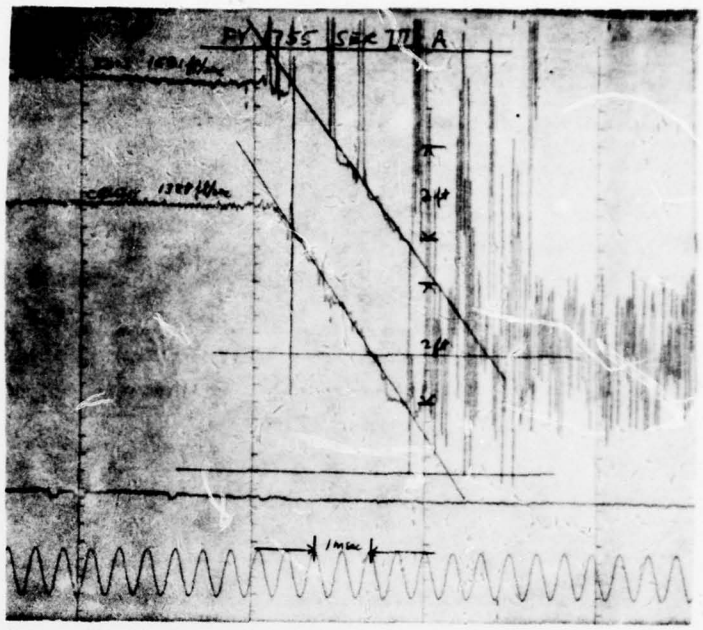


Figure 21. FY-1755, Series III A.

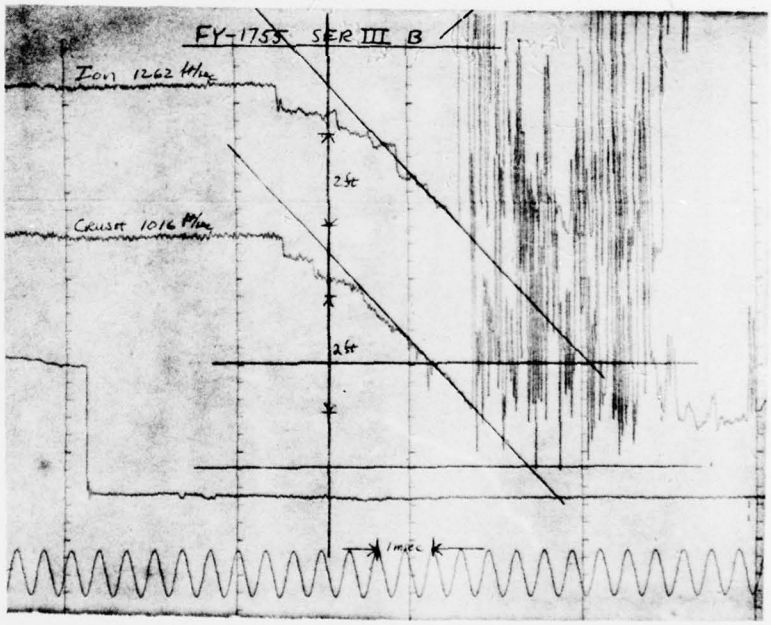


Figure 22. FY-1755, Series III B.

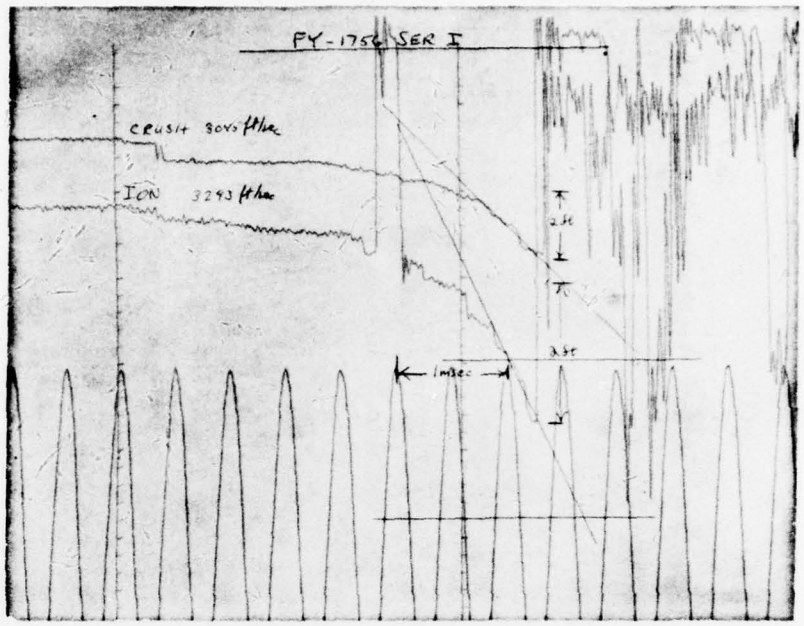
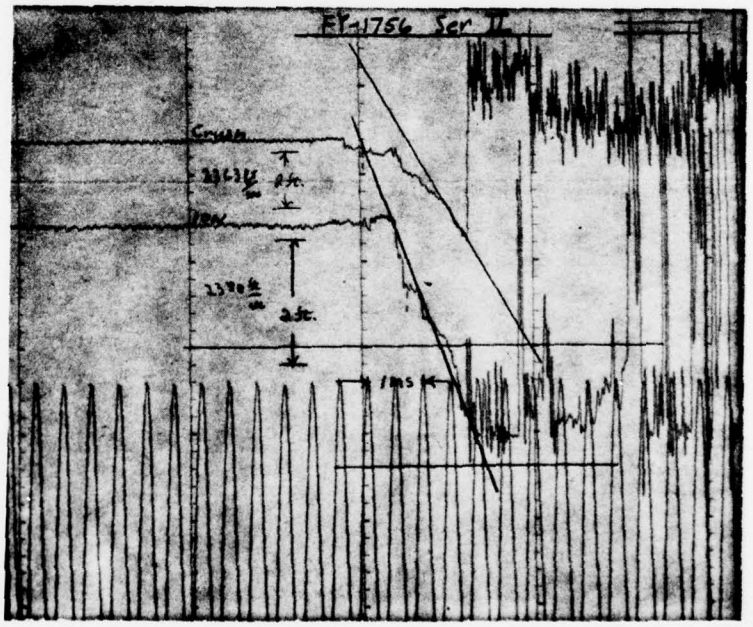


Figure 23. FY-1756, Series I.



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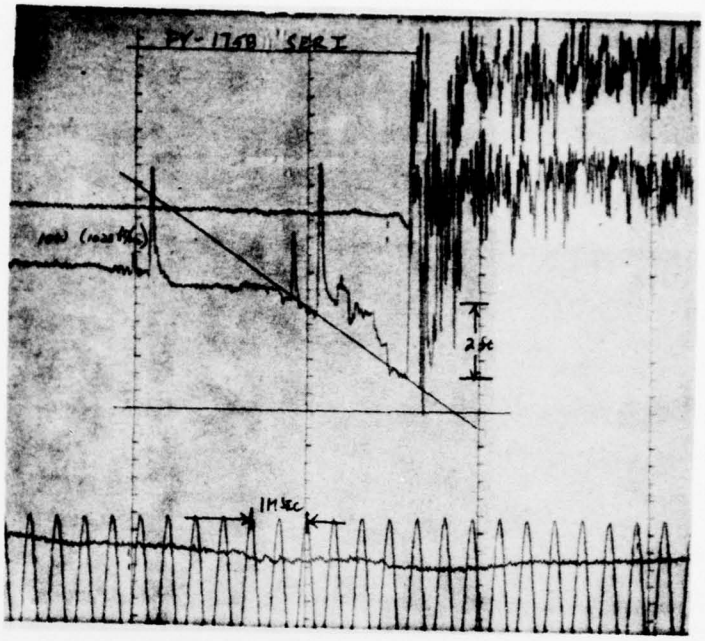


Figure 25. FY-1758, Series I .

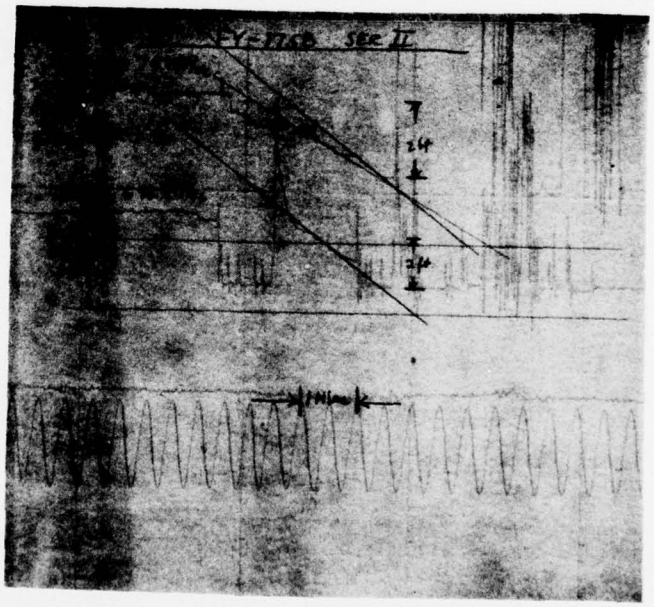


Figure 26. FY-1758, Series II.

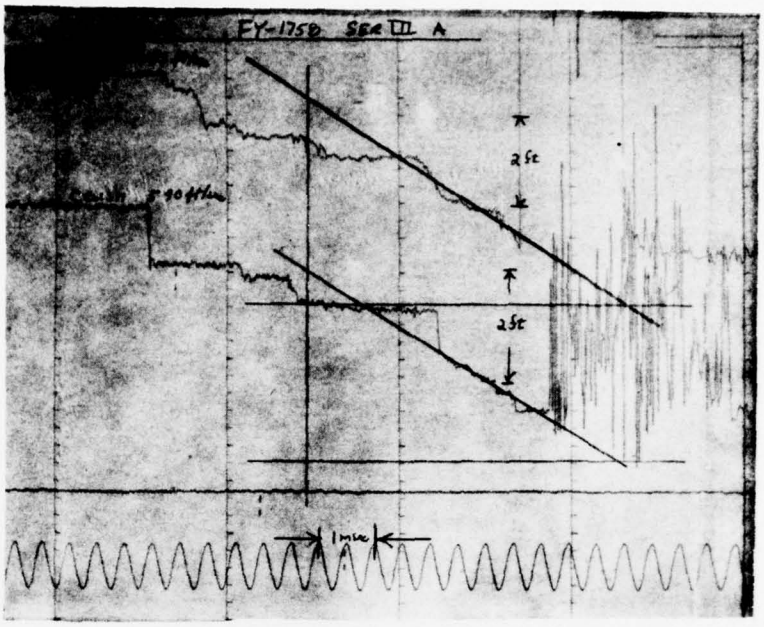


Figure 27. FY-1758, Series A.

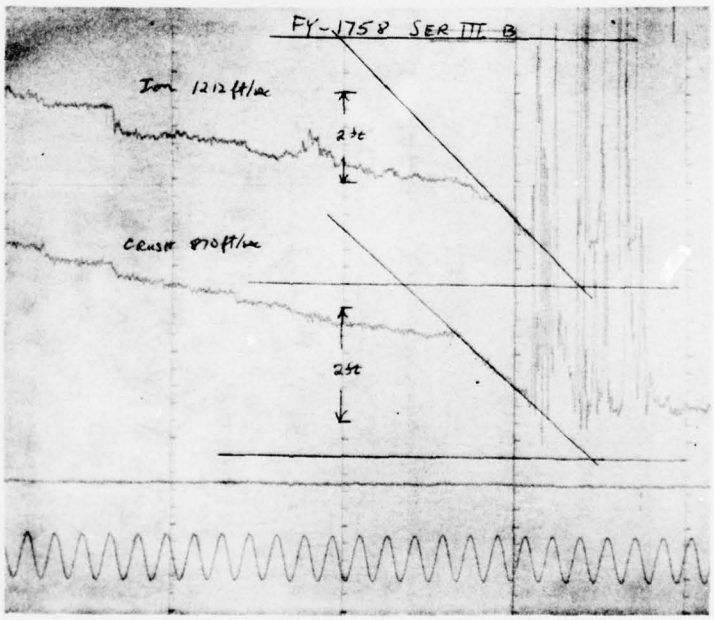


Figure 28. FY-1758, Series III B.

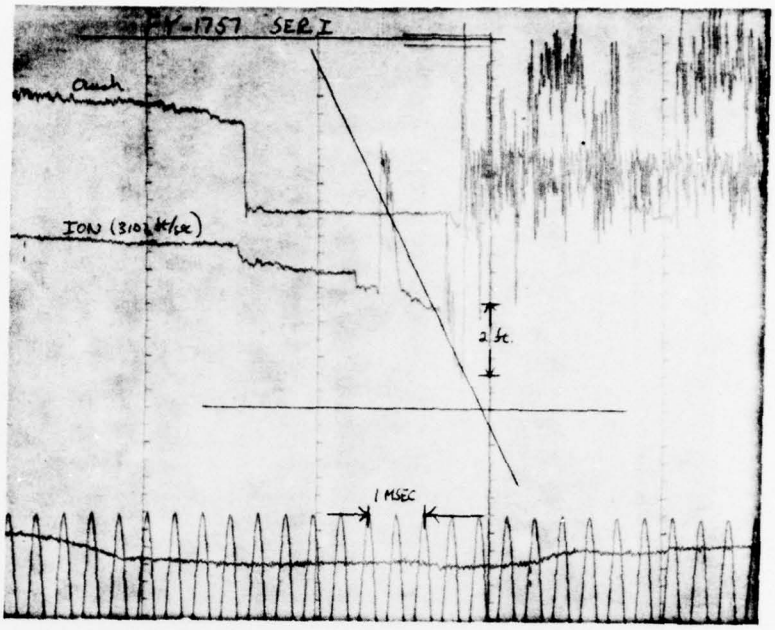
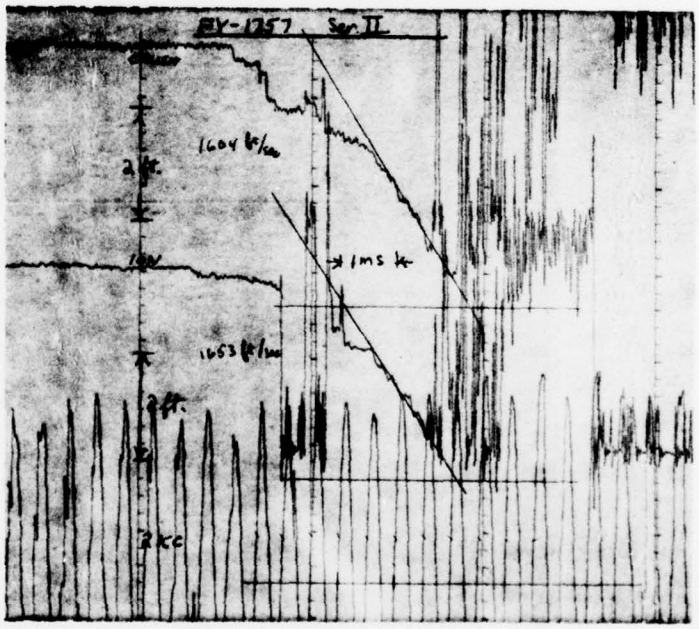


Figure 29. FY-1757, Series I.



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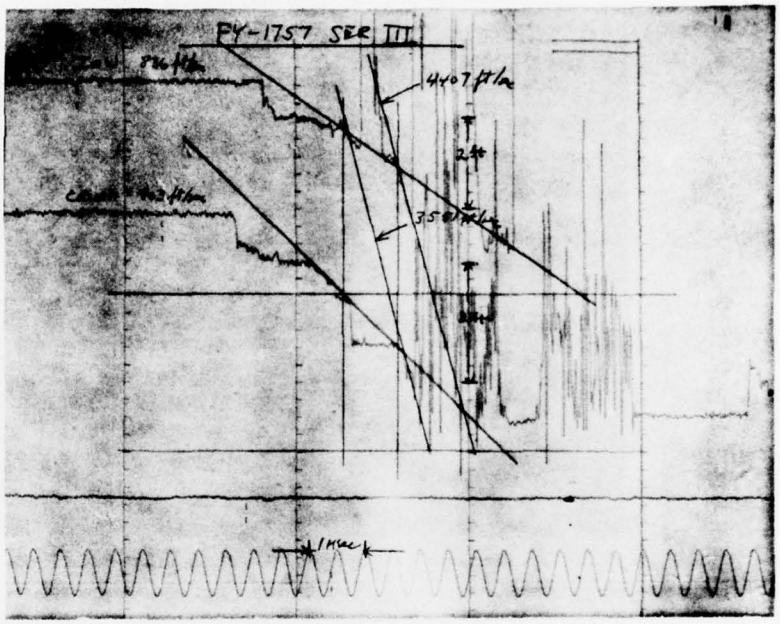

Figure 31. FY-1757, Séries III.

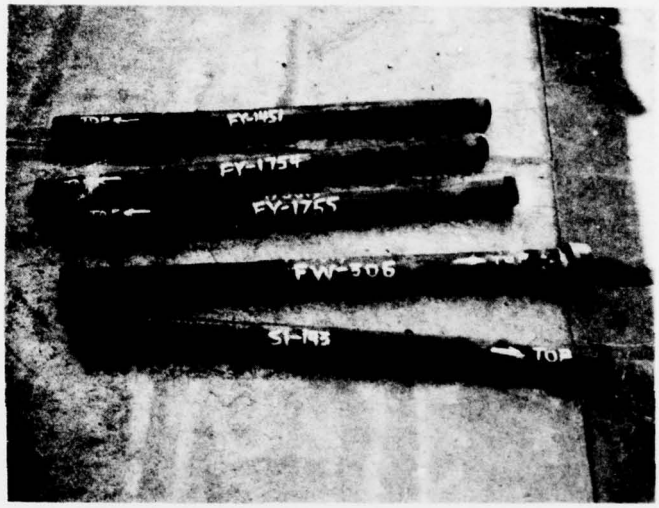

Figure 32. Typical pipes that did not fail.

FY-1757 series

FY-1757 series

Figure 33. Typical pipe failure (test 2).

Slow rate

Fast rate

Figure 34. Pipe damage from PFP-555 series.

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