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LARGE-SCALE STUDIES OF GAS DETONATIONS

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

November 1968

LARGE-SCALE STUDIES OF GAS DETONATIONS

By D. S. Burgess, J. N. Murphy, N. E. Hanna,
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This publication has been cataloged as follows:

Burgess, David S

Large-scale studies of gas detonations, by D. S. Burgess [and others. Washington] U. S. Dept. of the Interior, Bureau Mines [1968]

53 p. illus., tables. (U. S. Bureau of Mines. Report of investigations 7196)

1. Gases. 2. Gas research. I. Title. (Series)

TN23.U7 no. 7196 622.06173

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

LARGE-SCALE STUDIES OF GAS DETONATIONS

by

D. S. Burgess,[1] J. N. Murphy,[2] N. E. Hanna,[3]
and R. W. Van Dolah[4]

ABSTRACT

The characteristics of gas-phase detonations were observed in 20 instrumented firings within earthen tunnels, in 100 such detonations in a 24-in-diam by 163-ft-long steel pipe, and in about 200 smaller scale firings. Most of the fuels studied were representative hydrocarbons--acetylene, propane, gasoline, and a roughly equimolar mixture of methylacetylene, propadiene, and propane.

In a pipe with two closed ends, the detonable limits were demonstrated to be very nearly the same as reported limits of flammability. The side-on impulses (pressures integrated over 200-msec intervals) were shown to be the same function of concentration regardless of whether deflagration or detonation had occurred.

In a pipe with only the initiation end closed, the impulses of all fuel-air systems tended toward the same level when averaged over comparable ranges of fuel concentration; the lower pressures with saturated hydrocarbons were nearly compensated by longer durations of pressure transient. In all fuel-air systems, unexpectedly high impulses were obtained with slightly lean mixtures.

In earthen confining structures, the impulse of the explosion was efficiently converted into momentum of the failing wall. In the configurations studied, an earth velocity of about 20 fps was critical to overcome the soil's resistance to shear. The destructive effect was determined by gas pressure rather than by total energy release.

The assignment of a "TNT equivalent" to an explosive gas mixture is discussed in terms of the confinement of the mixture.

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INTRODUCTION

The investigator of a gas explosion is often hard put for guidelines as to whether a detonation may have occurred. The diagnosis of "detonation" or of "deflagration" usually depends on such secondary observations as the fracture lines of a metal part[5] or the periodicity of breaks in a pipe.[6] Likewise, the safety engineer whose function is to predict the likelihood of a gas detonation or the consequences of such a disaster may be equally short of basic information.

To assist in such problems, we have reviewed some gas detonation data resulting from recent supporting investigations for the Department of Defense.[7] These studies comprised about 300 gas explosions, ranging in scale from 3 to 3,000 ft^3 of gas mixture contained in cylindrical chambers ranging from 0.27 to 15 ft^2 in cross section and from 12 to 163 ft in length. The experimental work has been arranged herein to bear on limits of detonability as compared with limits of flammability; on the impulse (pressure-time integral) to be expected with hydrocarbon-air mixtures as functions of mixture strength and of confinement geometry; and on the effects of oxygen enrichment of fuel-air systems. To provide one illustrative example of the effects of detonations on confining structures, we present some findings on the movement and breakage of overburden when the detonating gas is confined in earthen tunnels. These data lead to a discussion of the "TNT equivalents" of explosive gas mixtures under varying conditions of confinement.

ACKNOWLEDGMENTS

We are happy to acknowledge our indebtedness to the Waterways Experiment Station, U.S. Army Engineers, for several fruitful conferences at Vicksburg, Miss., and for experimental data quoted in table 21 of this report; to the Lawrence Radiation Laboratory, Livermore, Calif., for discussions of the effects of cratering explosives and for some computations of detonation product composition; and to Picatinny Arsenal, Dover, N. J., for the intelligent guidance of our research, permitting many observations which we consider to be of general usefulness.

We are particularly grateful to Combustion and Explosives Research, Inc., Pittsburgh, Pa., for providing the authoritative advice of Dr. S. R. Brinkley, Jr., on the prediction of gas detonation parameters. The thermochemical computations of tables 1 and 2 were achieved through the loan of a computer program which Dr. Brinkley was currently in the process of developing.

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[5] Zabetakis, M. G. Explosion of Dephlegmator at Cities Service Oil Company Refinery, Ponca City, Oklahoma, 1959. BuMines Rept. of Inv. 5645, 1960, 16 pp.

[6] Armistead, George, Jr. Safety in Petroleum Refining and Related Industries. Simonds, New York, 2d ed., 1959, p. 43. The subject is also well covered in a 16-mm motion picture, "Detonations," supplied by the American Oil Co., Whiting, Ind.

[7] Project numbers 1B543603D43103, dated December 1965, and 1B543603D43106, dated November 1967.

TABLE 1. - Product yields of four combustion processes of stoichiometric acetylene-air

	Bomb calorimeter	Open flame	Constant volume explosion	Detonation[1]
Final temperature, ° K........	298	2,537	2,918	3,230
Final pressure, atm..........	1	1	9.78	19.56
Composition, mole fraction:				
H_2O......................	.081	.071	.064	.054
H_2.......................	-	.004	.005	.008
CO_2......................	.161	.119	.099	.075
CO.........................	-	.039	.056	.078
N_2.......................	.758	.736	.722	.703
O_2.......................	-	.002	.020	.024
OH.........................	-	.016	.012	.018
H..........................	-	.007	.003	.008
O..........................	-	.002	.004	.011
$-\Delta H_{298}$, cal/g................	842	692	630	550

[1] Equation 12.

TABLE 2. - Computed pressures, p_v, in combustion of acetylene in air and in oxygen-enriched air

(Initial pressure and temperature, 1 atm at 298° K)

Acetylene, fraction of stoichiometric	Oxygen, pct				
	20.9	25	33	50	100
0.50..................	7.29	7.80	8.78	10.41	13.29
1.00..................	9.78	10.41	11.48	13.16	17.09
1.25..................	10.38	11.18	12.41	13.75	-
1.50..................	10.75	11.65	13.04	14.30	-
1.75..................	10.99	-	-	-	20.49
2.00..................	-	-	-	16.54	18.46
2.50..................	11.2	-	-	-	-

Much of the experimental work reported below was performed by Robert H. Mattes, Howard R. Grainger, Arthur J. Slaypoh, and John A. Brandis. Other contributors from the Explosives Research Center and from the Health and Safety Research and Testing Center of the Bureau of Mines are too numerous to acknowledge individually.

BACKGROUND

Limits of Detonability

As recently as 1955 it was proposed that detonable gas mixtures included only those that had positive pressure exponents of burning velocity,

$$S_u = kp^n . \tag{1}$$

As such a gas mixture burns in a closed vessel its burning velocity, S_u, must increase monotonically with increasing pressure, leading to a runaway pressure increase. From the data that were available in 1955, the pertinence of equation 1 seemed entirely reasonable. However, in subsequent years it became apparent that fewer gas mixtures exhibit positive n and that many more gas mixtures could be detonated than was previously supposed. A consensus has gradually developed that almost any gas mixture that is flammable is also detonable if initiated with a sufficiently energetic source. A recent Report of Investigations[8] shows the broadening of the detonable limits of acetylene-oxygen as the mixtures are initiated by increasingly energetic sparks.

Pressures and Impulses in Gas Detonations

In this section we draw upon a postulated detonation wave structure which found acceptance during the first half of the 20th century and which was associated with the names of Chapman and Jouguet, Zeldovich, von Neumann, Doering, and G. I. Taylor. We assume a steady, one-dimensional phenomenon propagating along the axis of a cylindrical vessel (tunnel) with no losses to the wall. An elementary gas volume which is overtaken by the detonation finds itself successively in five zones:

1. A shock front moving at detonation velocity, D, and raising the gas pressure to a high value (the von Neumann spike) which persists through the ignition delay period of the mixture.

2. A chemical reaction zone terminating after a few microseconds at the so-called Chapman-Jouguet (C-J) plane.

3. An isentropic expansion zone with a duration which is a direct function of tunnel length.

4. A static gas zone (pertinent only to closed-end tunnels) which endures until pressure is relieved by some failure of the confining walls.

5. A rarefaction during which the gases move toward the opening to the atmosphere and pressure falls toward ambient level.

These successive stages of the detonation are shown in a plot of pressure versus time (fig. 1). Numerical values are pertinent to a stoichiometric (7.75 percent) acetylene-air mixture at a distance of 60 ft from its initiation point at the closed end of a 150-ft-long tunnel. The other end of the tunnel is assumed to be open. Detonation velocity is taken as 1,830 m/sec or 6 ft/msec.

1. In figure 1 initiation is represented by point A and the detonation front reaches the instrumented volume element at B after 10.0 msec. The pressure rises to 34 atm within the time of a few molecular collisions (about 10^{-9} sec) and the ignition delay extends to about 10^{-6} sec. Thus, the impulse

[8] Litchfield, E. L., M. H. Hay, and D. J. Cohen. Initiation of Spherical Detonation in Acetylene-Oxygen Mixtures. BuMines Rept. of Inv. 7061, 1967, 6 pp.

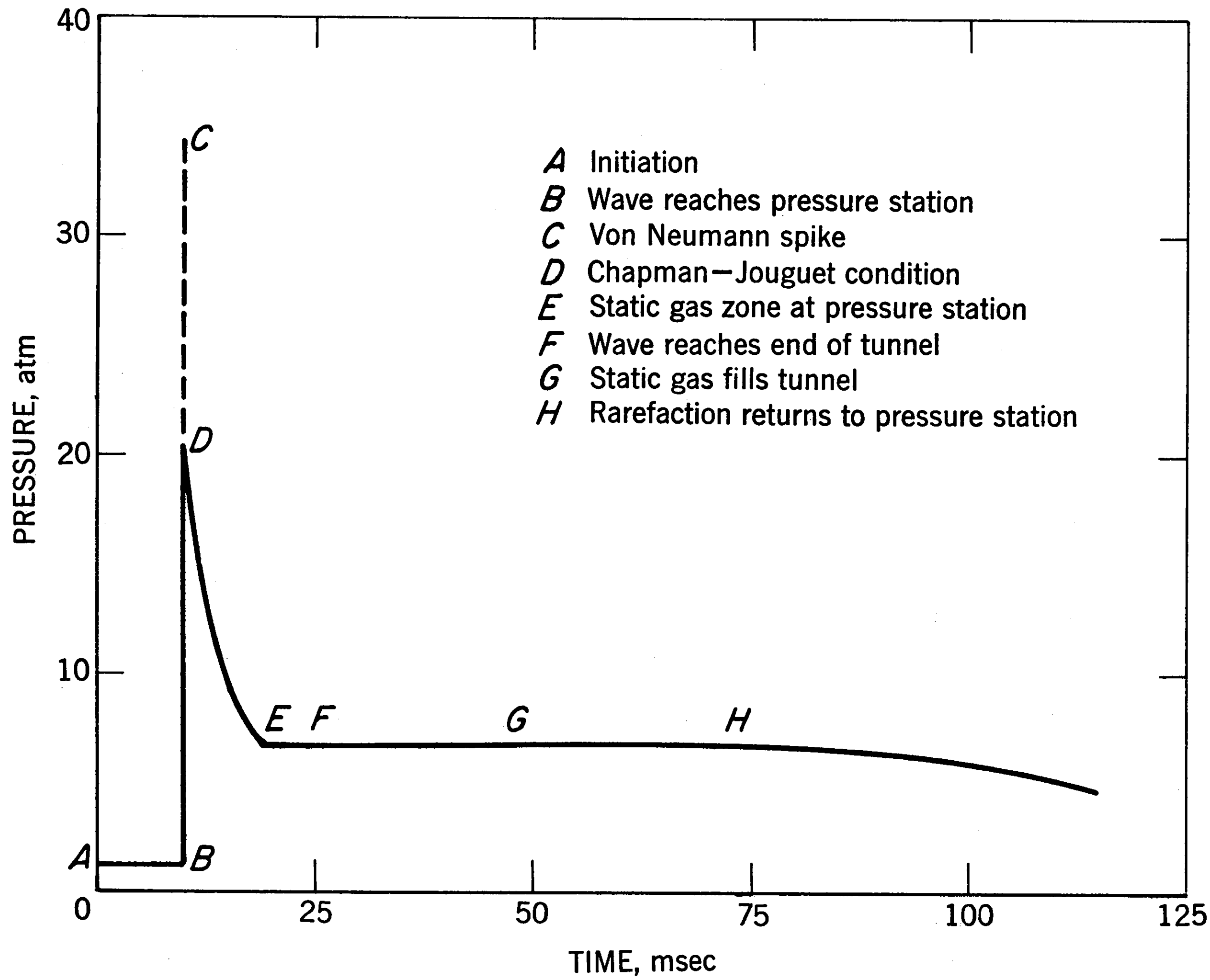

FIGURE 1. - Pressure-Time Transient in Stoichiometric Acetylene-Air Mixture. Steel tunnel with initiation end closed. Instrument station 60 feet from initiator point.

represented by this spike is 34 atm x 14.7 psi/atm x 10^{-6} sec or 5 x 10^{-4} psi sec, which is insignificant.

2. After the ignition delay chemical reaction runs its characteristic course (not necessarily to completion) at the C-J state in a few microseconds.[9] In this process, the pressure falls to 19 atm at point D in figure 1. Assuming pressure to be a linear function of time, the impulse during a 10-μsec reaction zone is $\frac{34+19}{2} \times 14.7 \times 10^{-5} = 4 \times 10^{-3}$ psi sec, which again is negligible. With current, commercial instrumentation one can measure the C-J pressure but not the von Neumann spike. The 19 atm in this case would be called the detonation pressure.

[9] Kistiakowsky, G. B., and P. H. Kydd. Gaseous Detonations. IX. A Study of the Reaction Zone by Gas Density/Measurement. J. Chem. Phys., v. 25, 1956, p. 824.

3. Behind the C-J plane the gas expands and from this point on we must take into account the length of the tunnel. If the tunnel were open at the initiation end, burned gas would be escaping at its sonic velocity; the gas must be at rest somewhere between the C-J plane where its forward velocity is +805 m/sec and the open end where its escape velocity is -920 m/sec; on a time-tested assumption that gas velocity decreases linearly with distance,[10] the point at which it comes to zero is 54 pct (that is, $\frac{920}{920+805}$) of the distance from initiation point to detonation front. The gas is assumed, further, to come to rest at the same point whether the tube is open or closed. This point, E, is reached in figure 1 when the front has traveled 60/0.54 = 111 ft, or gone 51 ft past our observation station. During this expansion, the static pressure falls from 19 to 6.7 atm and the area under the pressure versus time curve from D to E is roughly $\frac{19+6.7}{2} \times 14.7 \times 0.0085$ or about 1.6 psi sec.

4. Beyond point E, the pressure is at a plateau value of 6.7 atm or 84 psig and remains there until relieved by heat losses or by some opening in the tunnel. In the 150-ft-long tunnel of figure 1, the detonation front should reach the open end at 25 msec, and static gas should fill the tunnel in $\frac{25}{0.54} = 46$ msec; thereafter, pressure relief requires another 30 msec for a rarefaction to return at sonic velocity to our pressure station. Thus the impulse associated with this part of the wave, EH of figure 1, is about 84 psig $\times$ (0.076 - 0.0185) sec, or 5 psi sec. This is usually the most destructive feature of the detonation and to achieve it the initiation end of the tunnel must be closed.

5. After the rarefaction has reached our observation point at 76 msec, pressure falls asymptotically to 0 psig. In the case of an unyielding structure this may require 100 msec and the pressure-time curve beyond H makes a substantial contribution to total impulse. In a yielding dirt tunnel, the walls or end closure will probably have moved sufficiently during this interval to provide faster pressure relief.

As the front moves down the tube, all detonation front properties--that is, pressure, gas density, temperature, detonation velocity, and gas velocity--remain constant. But the distance scale stretches linearly with time, so the side-on impulse against any point in the wall is proportional to its distance from the point of initiation. This explains the periodic breaks in long pipes,[11] each break serving as a new open end and requiring additional wave travel for the impulse to build up again. Likewise the end-on impulse at the closed end of a pipe is linearly proportional to the distance that the wave has traveled. The reflected pressure is related to the static pressure of figure 1 by

$$\frac{p_r}{p} \approx 2.55. \qquad (2)$$

[10]Taylor, G. I. The Dynamics of the Combustion Products Behind Plane and Spherical Detonation Fronts in Explosives. Proc. Roy. Soc., v. 235, 1950, p. 235.

[11]Work cited in footnote 6.

In the detonation of stoichiometric acetylene-air which has been used for illustration, the reflected pressure at a closed downstream end is about 750 psig; the end-on impulse is always higher than the side-on impulse at the same distance of wave travel.

Energy Release and TNT Equivalents

Since the "chemical energy" of an explosion seems to have been subject to various definitions, some illustrative examples are given below for the stoichiometric mixture of acetylene-air at 1 atm, 298° K.

When a detonation wave passes through this mixture, the product composition at the C-J plane is approximately as given in the final column of table 1. If these products could be returned to ambient conditions without change in composition the enthalpy change of the reaction would be

$$\Delta H_{298} = H_{298} \text{ (products) } - H_{298} \text{ (reactants) } = -550 \text{ cal/g of mixture.} \qquad (3)$$

Since the detonation front is more nearly a constant volume than a constant pressure process, the "chemical energy" should better be given by ΔE, the change in internal energy. But

$$\Delta E_{298} = \Delta H_{298} - \Delta n\, RT, \qquad (4)$$

where Δn is 0.02 mole per mole of initial mixture, R is 2 cal/mole ° K, and T is 298° K, which gives 12 cal/mole for Δn RT or 0.4 cal/g of mixture. Thus the above ΔH of -550 cal/g may be used interchangeably with ΔE as the energy release which determines C-J pressure (point D of fig. 1) as well as temperature, density, and detonation velocity.

Also, it has been pointed out that the maximum work that can be done by the expanding product gases is given by the change in Helmholtz free energy or work content.[12]

$$-\Delta A = -\Delta E + T\Delta S. \qquad (5)$$

The $T\Delta S$ term above is significant when there is a large change in molecular weight. But for acetylene-air going to detonation products its value is only 7 cal/g. Thus, for hydrocarbon-air mixtures that contain upwards of 70 percent unreacted nitrogen, we use the approximation

$$\Delta A \simeq \Delta E \simeq \Delta H. \qquad (6)$$

Now as the product gases expand adiabatically behind the C-J plane, the dissociated species recombine releasing more heat. Table 1 shows that $-\Delta H_{298}$ increases to 630 cal/g at the pressure of a constant volume combustion (col. 4) and to 692 cal/g at atmospheric pressure (col. 3). This added energy, or some part of it, contributes to the blast effect of an acetylene-air explosion;

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[12] Kinney, G. F. Explosive Shocks in Air. The Macmillan Co., New York, 1962, pp. 10-18.

since there is no convenient temperature and pressure at which the exothermic recombinations may be said to terminate, we must compute ΔH_{298} for complete conversion to CO_2 and H_2O (col. 2) getting -842 cal/g.

To assign an equivalent weight of TNT to a known weight of acetylene-air, we note that on complete combustion of TNT in excess oxygen

$$C_7H_5N_3O_6 + O_2 \text{ (excess)} \rightarrow 7\ CO_2 + 5/2\ H_2O + 3/2\ N_2 - 3{,}600\ \frac{\text{cal}}{\text{g}}, \tag{7}$$

while on explosion in an inert gas environment,[13]

$$C_7H_5N_3O_6 \rightarrow 3.7\ C + 2\ CO + 1.3\ CO_2 + 0.1\ CH_4 + 0.5\ H_2$$
$$+ 1.6\ H_2O + 1.3\ N_2 + 0.2\ NH_3 - 1{,}093 \pm 5\ \text{cal/g}. \tag{8}$$

Thus, if a small weight of TNT is exploded within a closed chamber, the resultant final pressure should vary by as much as 3,600/1,093 or a factor of 3.3 depending on whether the chamber contains excess air. This is illustrated by figure 2, reproduced from a paper by Weibull,[14] which gives pressures in four vented chambers (open symbols) as a function of charge-volume ratio (lb TNT per ft^3 of volume); the ordinate $p_m(o)$ is analogous to the pressure of constant volume combustion if the same chambers were filled with explosive gas mixtures. We have fitted a dashed line

$$p_m(o) = 800\ \frac{Q}{V}\ \text{atm} \tag{9}$$

through Weibull's data for small TNT charges in large chambers and a dotted line

$$p_m(o) = 240\ \frac{Q}{V}\ \text{atm} \tag{10}$$

through data for large charge-volume ratio. Note that 800 and 240 are in the same ratio of 3.3 to 1.

Now, stoichiometric acetylene-air with a density of 0.080 lb/ft^3 gives a $p_m(o)$ of 9.78 atm (col. 4, table 1). According to equation 9 the equivalent TNT loading is 0.0122 lb/ft^3. Thus, 1 lb acetylene-air is equivalent to 0.0122/0.080 or 0.153 lb TNT exploding in excess air. By equation 10, 0.080 lb acetylene-air is equivalent to 0.041 lb TNT exploding in the absence of ambient oxygen or 1 lb gas mixture is equivalent to 0.5 lb TNT.

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[13] Ornellas, D. L. The Heat and Products of Detonation of HMX, TNT, NM and FEFO. Paper presented at 154th National Meeting of the American Chemical Society, Symposium on Detonations and Reactions in Shock Waves, Sept. 12-13, 1967.

[14] Weibull, Hans R. W. Pressures Recorded in Partially Closed Chambers at Explosion of TNT Charges. Presented at the New York Academy of Sciences Conference on Prevention of and Protection Against Accidental Explosions of Munitions, Fuels and Other Hazardous Mixtures, Oct. 10-13, 1966.

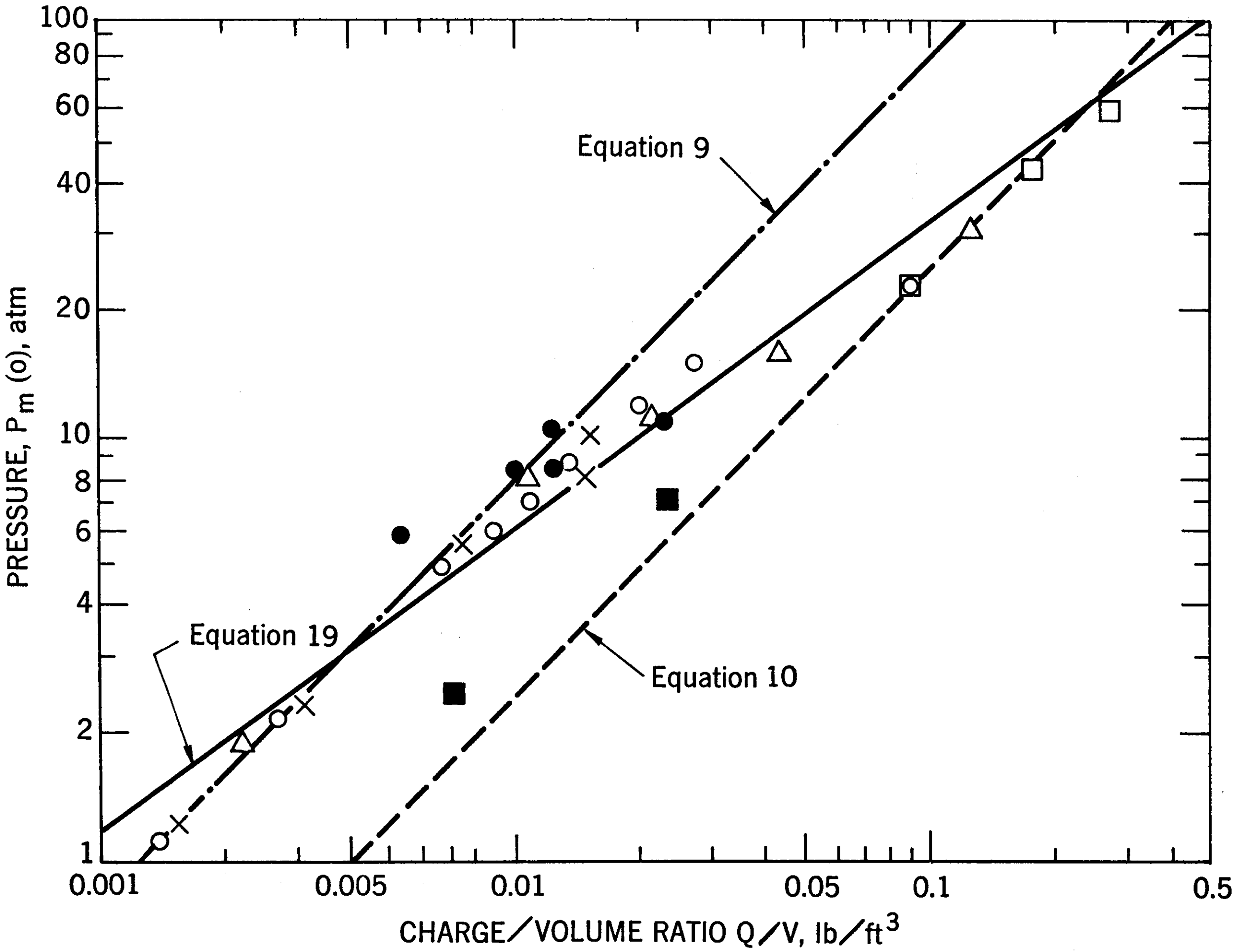

FIGURE 2. - Pressures Recorded in Chambers by Weibull Using TNT and in the 50-M Steel Tunnel Using Detonating Cord.

Using ΔH_{298} = -842 cal/g from column 2 of table 1 and comparing this figure with -3,600 and -1,093 cal/g for TNT with and without excess air, we would obtain the TNT equivalences of 0.23 and 0.77 lb TNT per pound of gas mixture. These values overestimate the empirical TNT equivalence of gas explosions by about 50 percent in this particular application.

The objective of estimating a TNT equivalent is usually to compute a distance, d_1, at which some specific blast pressure occurs from the equivalent weight of explosive, W_1. This is related to the distance, d, at which the same blast pressure occurs from a real weight of TNT, W, by

$$\left(\frac{d}{d_1}\right) = \left(\frac{W}{W_1}\right)^{1/3} \tag{11}$$

Thus, an overestimate of 50 percent in W_1 leads to an overestimate of about 15 percent in computed safe distance.

Estimation of Detonation Parameters

In the Wave Front

The simplest way to estimate the detonation (C-J) pressure of a gas mixture is by an approximation given by Zeldovich,[15]

$$p_2 = 2\ p_v, \tag{12}$$

wherein p_v is the pressure of constant volume combustion. Numerous sources are available[16] giving p_v for various hydrocarbon-oxygen-nitrogen systems at initial pressures from 1 to 20 atm. For mixtures that cannot be found in these references, one can use a computational method such as that described by Gaydon and Wolfhard[17] to obtain values of any required accuracy with a desk calculator. Table 2 gives computed p_v for acetylene mixtures of varying stoichiometry and oxygen index.[18] Figure 3 shows p_2 as a function of mixture strength in acetylene-air, based on table 2 and equation 12.

The obvious shortcoming of the Zeldovich approximation is the implicit assumption that product composition is the same at pressures p_2 and p_v; this assumption is belied by columns 4 and 5 of table 1. A more rigorous method[19] for p_2 is given by

$$\frac{p_2}{p_1} = \frac{1 + \gamma_1\ (D/c_1)^2}{1 + \gamma_2}, \tag{13}$$

wherein p_1, γ_1, and c_1 are pressure, ratio of specific heats, and sound velocity in the unreacted mixture, all available from handbooks. The virtue of equation 13 is that specifying D and γ_2 effectively fixes the energy release at the C-J plane. Detonation velocity, D, is the easiest variable to measure with a candidate gas mixture and many values are available in the literature.[20] However, γ_2, the specific heat ratio in the reacted gas, must be estimated in some way; since the products include about 72 percent N_2 as well as other diatomic species such as CO, H_2, O_2, and OH, we first referred to specific heat tables and predicted that $\gamma_2 = 1.28$. This number used in equation 13 gave the dashed line in figure 3.

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[15] Zeldovich, Ya, and A. S. Kompaneets. Theory of Detonation. Academic Press, New York, 1960, p. 84.

[16] Steffenson, R. J., J. T. Agnew, and R. A. Olsen. Tables for Adiabatic Gas Temperature and Equilibrium Composition of Six Hydrocarbons. Purdue Univ. Eng. Ext. Ser. 122, May 1966, 98 pp.

[17] Gaydon, A. G., and H. G. Wolfhard. Flames, Their Structure, Radiation and Temperature. The Macmillan Co., New York, 1960, pp. 283-301.

[18] Computed by E. Cook of the Explosives Research Center using a Fortran program loaned to the Bureau by Combustion and Explosives Research, Inc.

[19] Weir, A., Jr., and R. B. Morrison. Equilibrium Temperature and Compositions Behind a Detonation Wave. Ind. and Eng. Chem., v. 46, 1954, p. 1056.

[20] Lewis, B., and G. von Elbe. Combustion, Flames and Explosions of Gases. Academic Press, New York, 1961, Ch. 8, pp. 511-555.

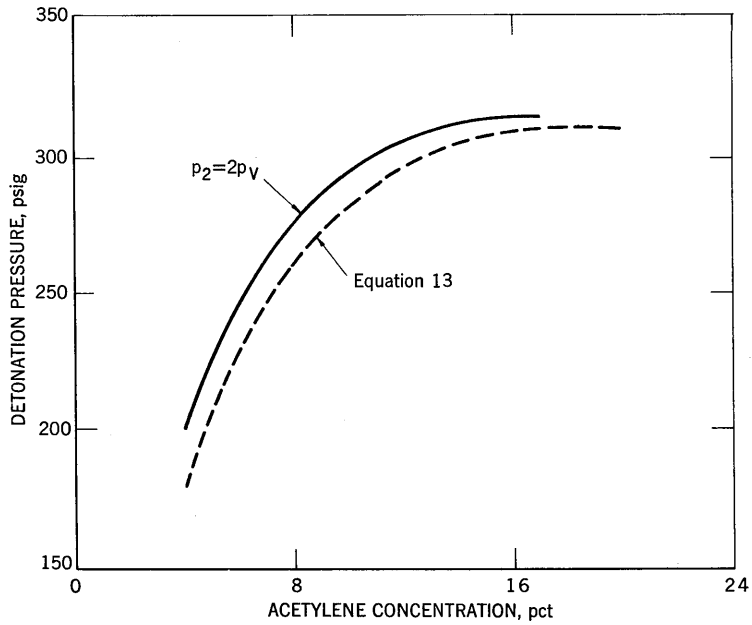

FIGURE 3. - Detonation (C-J) Pressure in Acetylene-Air Mixtures by Two Computational Methods.

However, a machine computation shows the appropriate value of γ_2 to be about 1.17[21] (because of shifting product composition) and with this "shifting gamma," equation 13 gives nearly the same prediction of detonation pressure as equation 12. Therefore, we consider the Zeldovich approximation to be entirely adequate for any practical purpose.

A Mollier-type diagram of dimensionless detonation parameters has been published by Dunn and Wolfson.[22] Any of the following quantities can be interpolated if two are known: D, γ_2, ρ_2, p_2, T_2, and B. B is an energy release function equal to $J\Delta E/c^2_1$, where J is the mechanical equivalent of heat. The simplicity of obtaining ΔE from measurements of D and p_2 is very attractive and a part of the Dunn and Wolfson chart is reproduced as figure 4. From this figure, p_2 is 19.4 atm, the energy release is about 650 cal/g of stoichiometric acetylene-air mixture, and the density ratio ρ_2/ρ_1 is 1.78.

In the Expanding Gases

To this point we have spoken of detonation parameters only at the C-J plane, but most of the impulse is found during and after the expansion of gases; that is, during intervals D-E and E-H of figure 1. For this we need the pressure of the expanding gases, calculated by the following steps:

1. Knowing D and ρ_2/ρ_1, obtain sound velocity at the C-J plane by

$$c_2 \rho_2 = D \rho_1 . \qquad (14)$$

In acetylene-air, c_2 = 1,830/1.78 = 1,025 m/sec.

2. Obtain the gas velocity at the C-J plane from

$$w = D - c_2 . \qquad (15)$$

In acetylene-air, w = 1,830-1,025 = 805 m/sec.

[21] See footnote 18.

[22] Dunn, R. G., and B. T. Wolfson. A Single Generalized Chart of Detonation Parameters for Gaseous Mixtures. WADC Tech. Note 57-263, 11 pp., ASTIA Doc. AD 130906.

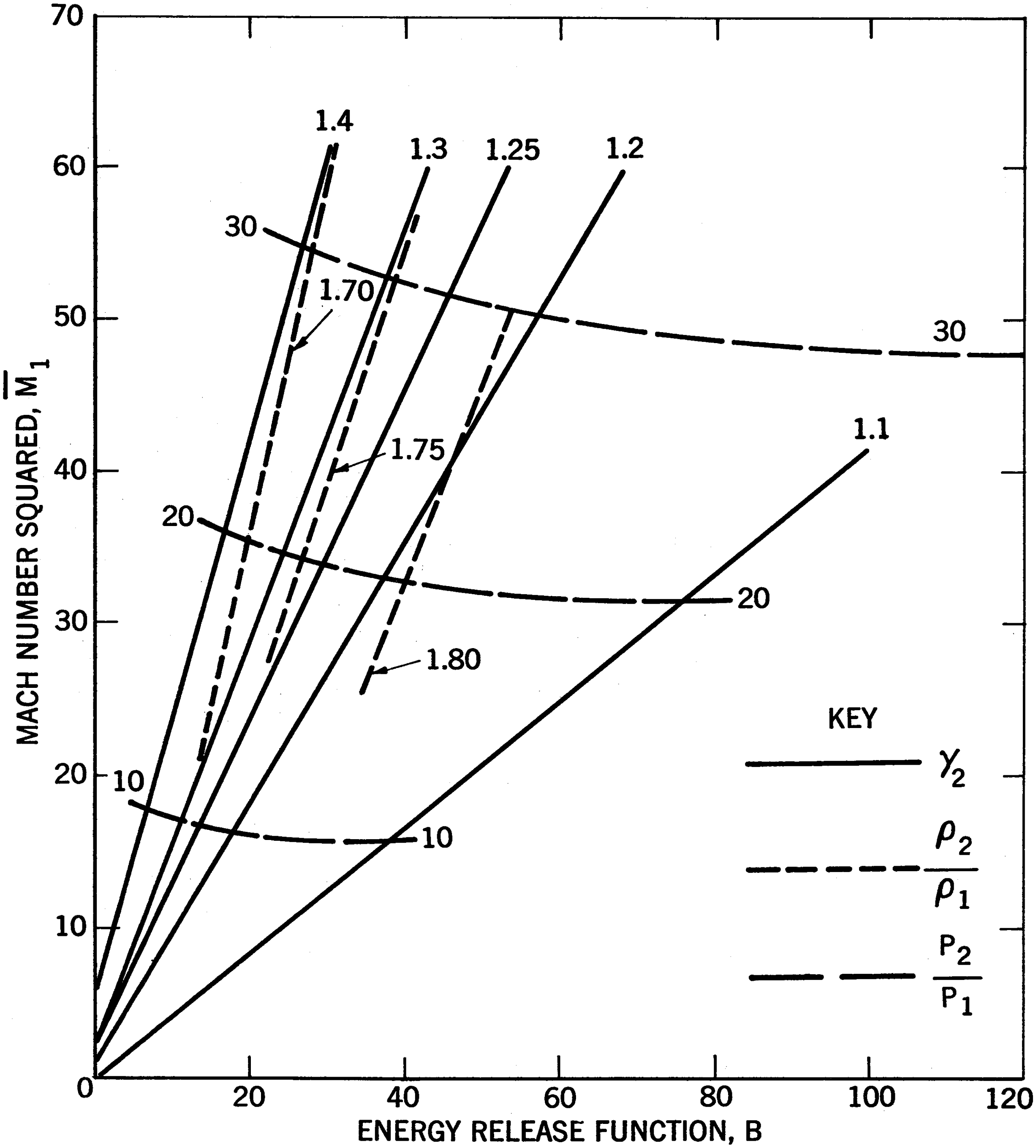

FIGURE 4. - Generalized Detonation Chart for γ_1 = 1.4.

3. Now obtain sound velocity at point E of figure 1 by

$$c_E = D - \frac{\gamma + 1}{2} w. \tag{16}$$

In acetylene-air, $c_E = 1{,}830 - \frac{2.17}{2}(805) = 920$ m/sec and assume that sound velocity decreases linearly with distance from c_2 to c_E.

4. Obtain the gas density ratio at points between the C-J plane and point E by

$$\left(\frac{\rho}{\rho_2}\right)^{\frac{\gamma - 1}{2}} = \frac{c}{c_2}. \tag{17}$$

5. Then the gas pressure at any point is given by

$$\frac{p}{p_2} = \left(\frac{\rho}{\rho_2}\right)^{\gamma}. \tag{18}$$

The outcome of this calculation was used to plot pressures in figure 1.

Fortunately, the errors resulting from a bad choice of gamma are somewhat cancelled in equations 16 and 17. Also, there should be little difference in gamma for two hydrocarbon-air systems expanding through comparable temperature ranges. With an assumed gamma of 1.26, the pressure of the expanded gas in the interval E-H of figure 1 is calculated to be 35 pct of the C-J pressure; with gamma taken to be 1.17, the expanded gas pressure is 41 pct of C-J pressure.

Fuel Selection

The hydrocarbons used in this study were acetylene, MAPP,[23] propane, and gasoline.

Acetylene stands near the top of the list of hazardous hydrocarbons because its high degree of unsaturation makes the fuel molecule endothermic. The contribution of endothermicity to its heat of detonation is illustrated by equation 3 in which the detonation products are those given in the final column of table 1.

$$\Delta H_{298} = H_{298}\text{ (products)} - H_{298}\text{ (reactants)} = -11.7\text{ (products)}$$
$$-4.1\text{ (acetylene)} = -15.8\text{ kcal/mole of mixture.} \tag{3}$$

Since so much of the heat of reaction comes from the endothermic fuel molecule, acetylene-air is very insensitive to mixture strength. Thus it exhibits wide limits of detonability and does not have a narrow peak of performance around an optimum concentration. As shown in figure 3, the detonation pressure of acetylene-air actually increases as the mixture is made very rich while most other fuels fall off in performance.

[23] Reference to trade names is for information only and endorsement by the Bureau of Mines is not implied.

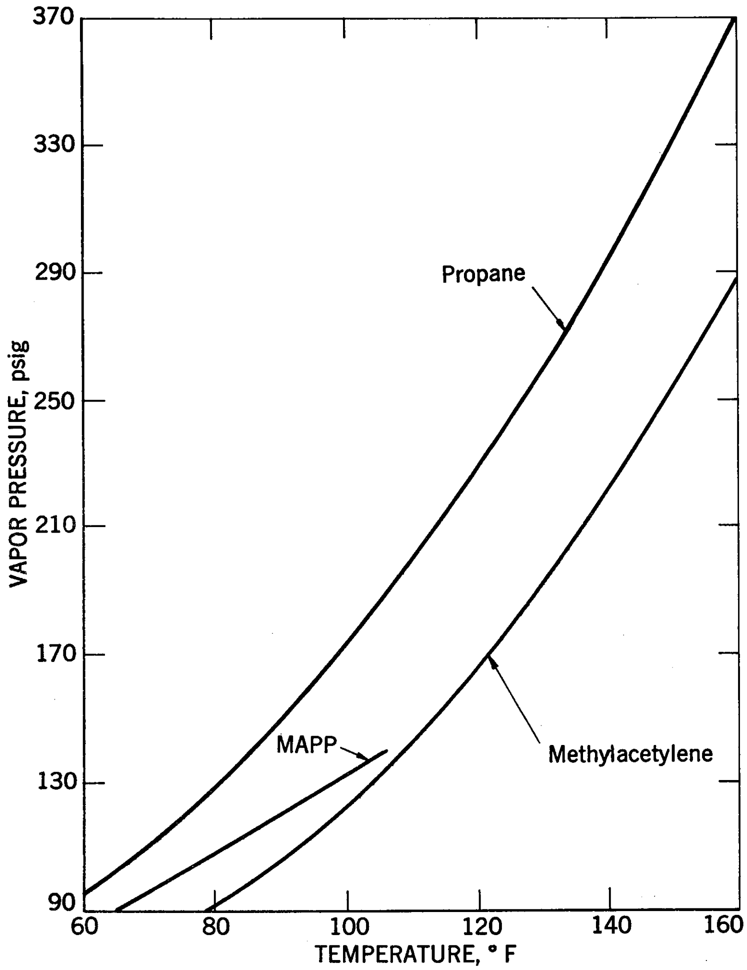

FIGURE 5. - Vapor Pressure as a Function of Temperature for Propane, Methylacetylene, and MAPP.

MAPP is a commercial hydrocarbon blend which is used as a fuel for cutting and welding. The samples used here contained almost equal fractions of methylacetylene, propadiene, and propane. Its overall endothermicity is about equivalent to that of ethylene and its physical properties are similar to those of propane or liquefied petroleum gas. A vapor pressure curve is given in figure 5,[24] and computed p_v in figure 6. Its dispersion into air or air-oxygen stream is shown schematically in figure 7, wherein the Mitey Mite is a gasoline-powered blower and the liquid oxygen converter is a device for supplying liquid oxygen at a constant pressure to a spray nozzle; both the oxygen and the MAPP vaporized in the air stream without accumulation of liquid.

Propane was metered through the same system by using a slightly different spray nozzle.

EXPERIMENTAL METHODS

Tunnels and Test Chambers

The Crawshaw-Jones Apparatus

Detonation velocities, limits of detonability, and impulses of various fuel-air mixtures were determined in a closed system by using the Crawshaw-Jones apparatus. A booster of PETN or tetryl was used as the initiating stimulus. The equipment includes a steel cannon with a borehole measuring 2 in in diam by 24 in in length. The cannon is bolted to a pipe of extra heavy lap-welded wrought iron which is 12 ft long and 7 in in diam with a capacity of 93 l. The far end of the pipe is closed with a 2-in-thick steel plate. A ½-in-diam sideline with a centrifugal blower for mixing the gases is attached near the ends. Pressure-sensitive probes, installed 79 in apart in the chamber wall, measured the propagation velocity of the deflagration or detonation.

[24] Courtesy of the Dow Chemical Co.

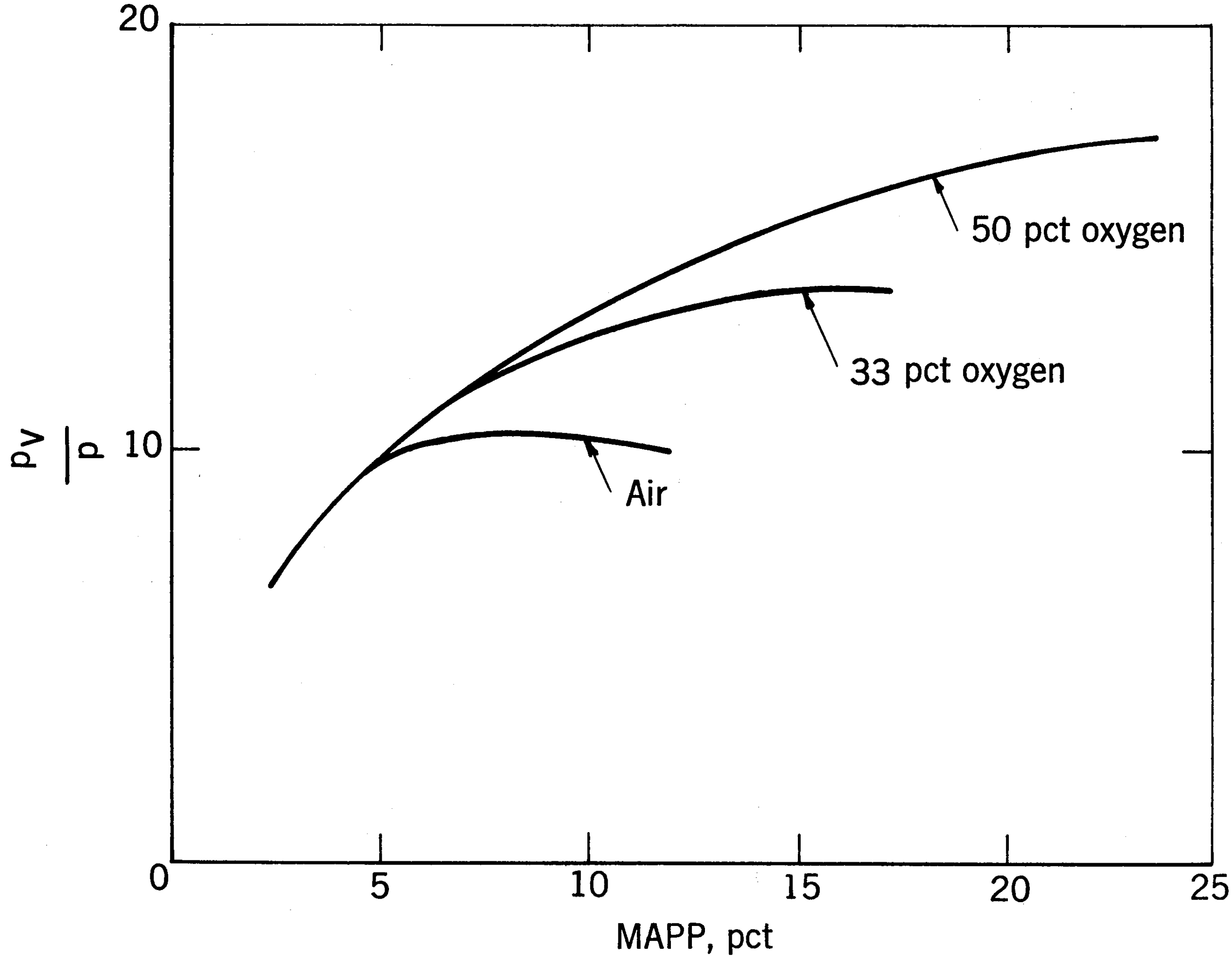

FIGURE 6. - Pressure Ratios on Constant Volume Explosion of MAPP Mixtures.

In preparing for an experiment, the apparatus chamber was thoroughly washed and dried. Large boosters (>10 g) were usually placed in the mouth of the cannon and small boosters were suspended in the pipe about 6 in from the cannon end. After coupling the pipe to the cannon, the chamber was evacuated to about 1 mm of mercury. The desired amount of gas was then introduced in the chamber by monitoring its partial pressure with a mercury manometer; supplemental oxygen, when used, was added in the same manner. Air was then added until the chamber reached atmospheric pressure. Mixing was effected by cycling the mixture through the side-arm unit for 10 min. Samples of the mixed gases were taken, just prior to firing, to determine mixture compositions. A gas-chromatographic analysis of the samples was usually in fairly close agreement with calculated mixture compositions. In some instances the cooled product gases were analyzed to determine the extent of the reaction.

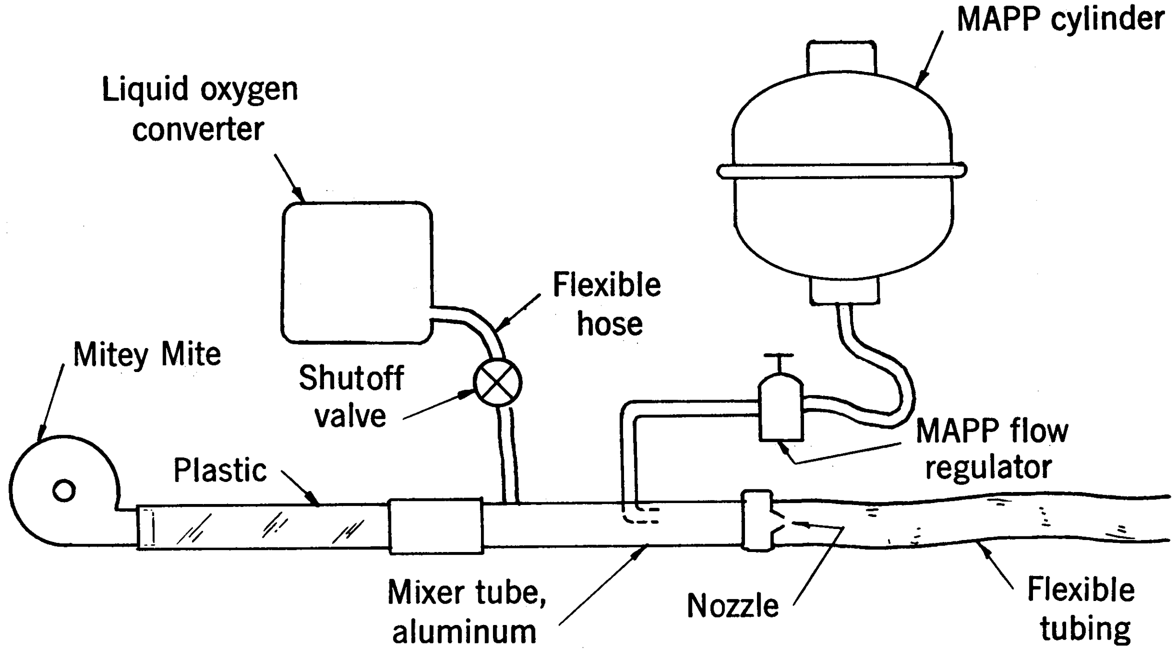

FIGURE 7. - MAPP-Liquid Oxygen Dispersion System.

Steel tunnel

In an effort to compare various explosive systems and to study such controlling parameters as concentration, point of initiation, and end confinement, a 2-ft-diam steel tube, 163 ft long, was constructed at Bruceton. The pipe was of a seamless variety with a 3/8-in wall. It was buried 2 ft underground with ends opening into concrete bunkers, to protect against brittle fracture in cold weather and to minimize the noise level. One end was flanged so that it could be closed with a steel plate. Instrumentation stations that included pressure transducers and gas sampling tubes were located at 26.5-ft intervals along the steel tunnel. A length of thin-walled plastic tubing at the open end of the tunnel served as a one-way valve to protect against gas dilution just prior to firing.

Acetylene, MAPP, propane, and gasoline, with and without supplemental oxygen, were fired in this facility. Suspended aluminum powder was included in certain shots. Detonating cord was used to compare condensed-phase and gas-phase explosions.

Hand-Dug Tunnels

To study earth movement in response to the pressure of a gas detonation, hand-dug tunnels were constructed by the sponsoring agency in a lateritic clay soil at Clark Hill Reservoir, S.C. The shear strength here was about 1,000 psf near the surface and 2,000 psf at a depth of 8 ft. A typical plan view of five of the seven tunnels is shown in figure 8. The cross sections were 3 ft wide by 5 ft high, and the overall length was 150 ft. Pressure transducers and accelerometers were installed at selected points along the tunnels by the

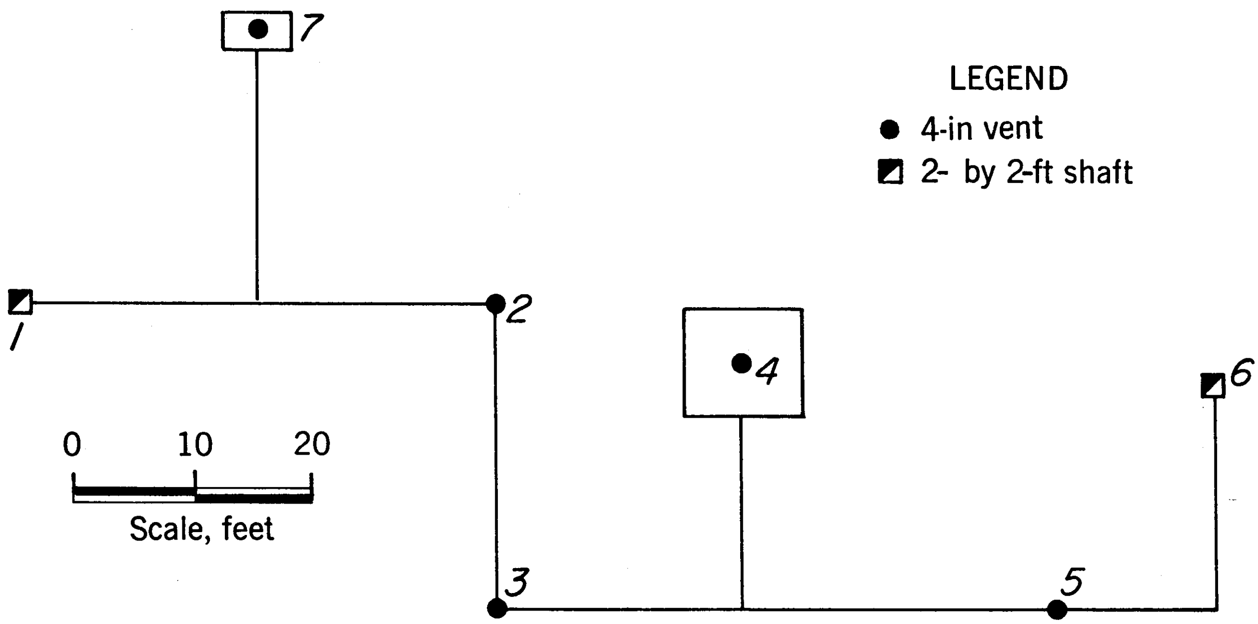

FIGURE 8. - Schematic of Typical Hand-Dug Tunnel Showing Gas Sampling Points and Rooms.

Waterways Experiment Station, and gas analysis was undertaken by use of combustible gas indicators.

Tunnels 1, 2, and 3 had 5 ft of overburden over approximately half of the tunnel and 8 ft over the remainder. Tunnels 1 and 2 were shot with acetylene-air mixtures; tunnel 3 was shot with an acetylene-air mixture supplemented by aluminum dust distributed over the tunnel floor. Bureau of Mines personnel were observers at these first three tests and were supplied with copies of pressure and acceleration data by Waterways Experiment Station. In subsequent tests at this site, the Bureau provided the explosive gas mixtures and Waterways Experiment Station continued their measurements of pressure and acceleration.

Tunnel 4 had an overburden of 6 to 8 ft and tunnel 5 had a uniform cover of approximately 8 ft. Tunnel 4 was loaded with a lean MAPP-air mixture and tunnel 5 with a lean MAPP-air-oxygen mixture.

Two other tunnels (6 and 7) had the same cross section as the other five but were straight runs, 70 ft long with no side rooms. They were dug at a greater depth than the other tunnels to provide overburden of greater competence. The excess topsoil was removed leaving 8 and 10 ft over tunnels 6 and 7, respectively. The shear strength of the deeper overburden was about 2,000 psf. MAPP-air mixtures were introduced as above and oxygen was added from cylinders.

Augered Tunnels

At a later stage in the program, a new set of tunnels was augered on a strip mine site near Paris, Pa. The location was provided by the

Weirton Ice, Coal and Supply Co. and had soil characteristics comparable to the South Carolina site described below. These tunnels were of 42-in diam and varied in length from 70 to 105 ft. To compare gas with condensed-phase explosives three tunnels were shot with ammonium nitrate-water slurries.

Instrumentation

Pressure Transients

In the beginning of the program all of the available pressure transducers were of the piezoelectric type. Although this type of transducer has the advantage of high-frequency response and good resolution, there are numerous disadvantages including ringing, overshoot, and base-line drift due to high thermal sensitivity and moisture (easily encountered in a field operation).

As discussed previously, a portion of the pressure wave of prime interest from the viewpoint of effect on structures is the part from D to H in figure 1. This calls for a transducer with good dc response and negligible base-line shift to accurately record the plateau and subsequent decay; this portion of the waveform contributes substantially to the total impulse. However, the transducer must first survive, and hopefully respond to, the high-pressure spike preceding the plateau. Although piezoelectric transducer-charge amplifier combinations have the necessary response, they have undesirable features for recording the low-frequency portion of the wave. To overcome this problem, pressure transducers of the bonded four-arm bridge strain-gage type having a 40-kc response and a 1,000-psi rating were obtained. The limiting frequency response was 1,000 cps due to insufficient amplification to drive higher frequency-low sensitivity galvanometers. However, the transducers performed as expected and gave good results particularly in observing the low-frequency portion of the waveform.

Pressure instrumentation in the Crawshaw-Jones apparatus was also required to follow low-frequency signals produced by the pressure plateau and still record the spikes produced by reflections in the chamber. A thin-film bridge-type pressure transducer was employed. Satisfactory results were obtained until the transducer failed due to a defective internal weld. The alternative transducer employed was a bonded four-arm bridge gage with a 10,000-psi rating. A sensor amplifier module was used to provide excitation and amplify the transducer output. In this case, the limiting frequency response of the system was 5,000 cps, the upper frequency of the galvanometer. The amplifier had a voltage amplification of 2,000, which was necessary to permit signals of less than 300 psi to be observed on a 10,000-psi full-scale transducer.

Detonation Velocity

The detonation velocity of the gas mixture was measured in two ways. When multiple pressure transducers were used in a tunnel or chamber, the arrival times of the detonation wave at two stations were observed on an oscillograph record; the velocity could be calculated from the distance between pressure transducers. Electronic counters were employed to improve accuracy. Small pressure-actuated gages were placed a few centimeters upstream from the other transducers. These gages synchronized oscilloscopes with the arriving detonation front. Two transducers were available specifically for measuring a time interval from which a velocity could be calculated. This technique gave more accurate results because the times could be measured to within 2 μsec.

Earth Movement

Earth displacement was measured from the upward movement of vertical stakes which were observed by Fastax camera against a stadia board background. The slope of the displacement-time record was one measure of earth velocity.

Earth velocity was also determined in several test series using strain-gage accelerometers with ranges of 0 to 100 g. To install the accelerometers, 3-in-diam vertical holes were drilled to a depth of several feet in the soil above the tunnel. An accelerometer was placed in the bottom of each hole which was then refilled with compacted earth. Integration of the acceleration-time record gave the earth velocity at a location above the axis of the tunnel and about halfway between the tunnel ceiling and ground surface.

Gas Sampling and Analysis

Whenever a gaseous explosive was used, gas samples were taken for analysis of fuel and oxidizer concentration and for evaluation of the distribution of the gases throughout the tunnel. Solenoid valves were employed for simultaneous sampling at several points immediately before firing. Usually, five 250-ml samples were taken in any given experiment. For example, in the 50-m steel tunnel, samples were taken at each of the five pressure-gage stations.

These gas samples were analyzed with a gas chromatograph or with an Orsat; the chromatograph used for the bulk of the analytical work had an accuracy and reproducibility of a few tenths percent.

EXPERIMENTAL RESULTS

Fuel Concentrations

Flow Regulation

When a tankful of volatile fuel is vaporized in the usual way, the temperature and vapor pressure drop to an extent which makes flow control difficult. Moreover, if the fuel is a hydrocarbon blend, the composition of the fuel may shift as the tank empties due to fractional distillation. This was avoided by standing the tank on its valve end so that liquid was forced into the vaporization line by its own vapor pressure. The flow was then regulated by the constriction of a spray nozzle and stayed essentially constant until the tank was empty.

It was also desired to provide two alternate flow rates, for use with and without supplemental oxygen. This was accomplished by a 1/16-in orifice which

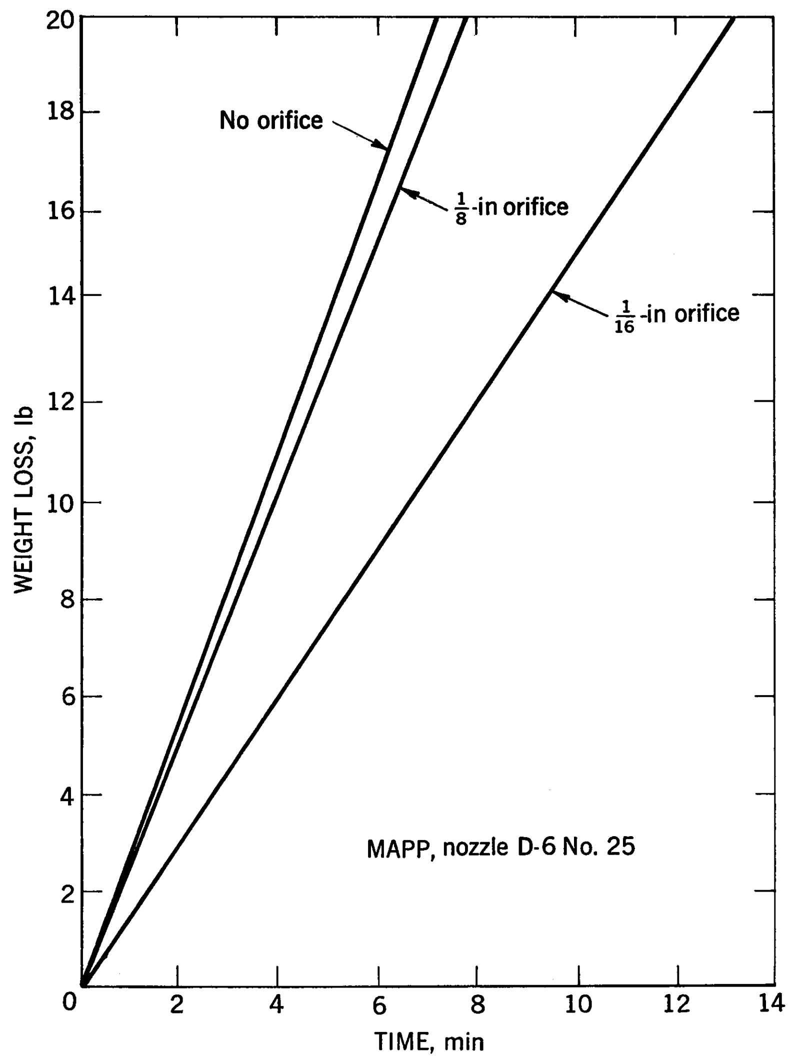

FIGURE 9. - Average Discharge Characteristics of MAPP From a D-6 No. 25 Nozzle and With a 1/8- or 1/16-In Orifice in the Liquid Line (ID 1/4 in).

could be valved into or out of the fuel line ahead of the spray nozzle. Inserting this orifice approximately halved the flows of MAPP and of propane (figs. 9 and 10).

Mixing and Losses in Tunnels

It was originally thought that gas mixtures could be induced to move through tunnels in "plug" flow, displacing air with very little mixing, so that one change of tunnel atmosphere would establish a proper fuel-air concentration. Our first disappointing evidence to the contrary was obtained in a covered trench constructed to simulate the South Carolina tunnels. A schematic of this trench is given in figure 8, its cross section being 3 by 5 ft, and its total volume 2,900 ft^3. The output stream of the gasoline-powered blower (260 cfm) was mixed with 29 cfm acetylene and fed into the trench at position number 1. In 10 min, there had been one change of volume and the anticipated acetylene concentration was 10 percent. Samples were taken immediately at the seven indicated positions and the concentrations, averaging 5.3 percent, are listed in table 3.

Since barely half of the added acetylene remained in the tunnel, a reassessment of previous experience was compiled as in table 4. Whenever samples had been taken after a single change of gas, only 50 to 70 percent of the added fuel could be accounted for. This could only mean that there had been circulating currents with extensive mixing. Sampling at the far end of the trench at time intervals from 1 to 10 min confirmed this. In plug flow no fuel should have been observed until the final minute, whereas in fact, fuel concentrations rose linearly with time from the first minute. Such channeling evidently developed from the high-velocity, small-diameter output stream of the blower. When the blower was replaced with an electric fan of about the

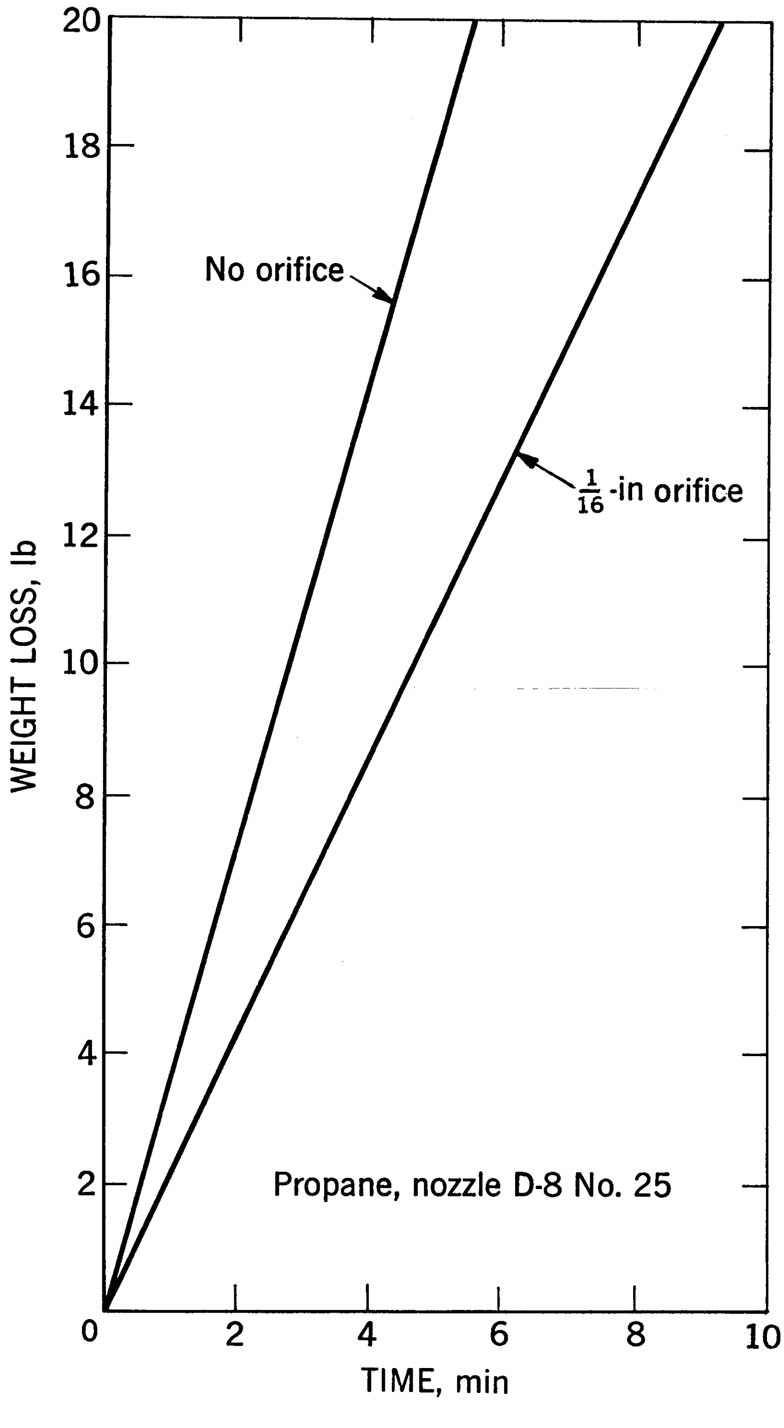

FIGURE 10. - Average Discharge Characteristics of Propane From a D-8 No. 25 Nozzle and With a 1/16-In Orifice in the Liquid Line (ID 1/4 in).

same diameter as the steel tunnel, concentrations varied with time as shown in figure 11.

TABLE 3. - Acetylene concentrations in 2,900-ft^3 tunnel loaded with 290 ft^3 acetylene

Sampling position[1]	Acetylene, pct	
	Direct	Difference
1	6.7	6.7
2	4.2	3.9
3	6.0	5.9
4	6.3	6.2
5	4.4	4.1
6	5.5	5.6
7	4.0	3.7
Average	5.3	5.2

[1] See figure 8.

In all experiments described below, fuel concentrations are those obtained by gas sampling rather than by flowmeter settings. The mixture was usually passed through the tunnel to give three volume charges, whereupon gas analysis usually confirmed the nominal fuel concentration.

Limits of Detonability, Detonation Velocities, and Impulses (Crawshaw-Jones Apparatus)

When a mixture of uncertain detonability is initiated with an explosive primer, a "wave" of ionization moves through the mixture at a velocity which characterizes the explosive reaction of the mixture. If the wave propagates at 1,500 m/sec or more, one is almost surely dealing with a gas detonation; if the wave velocity is about 1,000 m/sec or less,[25] one has only a shock, decoupled from subsequent combustion reactions. Thus, the concentration limits of detonability are usually apparent from a plot of wave velocity versus concentration. In figure 12, the detonable range is about 2.4 to 13.7 percent MAPP when 10 g PETN is used as initiator.

TABLE 4. - Experience with adding fuel-air mixtures to tunnels in one change of volume

Test No.	Anticipated, pct	Found, pct	Found, nominal	Remarks
Steel tunnel:				
25..................	15	8.3	0.55	
21..................	10	6.0	.6	
15..................	15	11	.73	1.5 changes.
Dirt (augered) tunnels:				
15..................	18.5	11	.59	
20..................	18.5	10	.54	
"Carolina" tunnel:[1]				
6..................	10	6.9	.69	
5..................	10	7.4	.74	1.5 changes.
4..................	10	5.0	.50	

[1] Backfilled trench constructed to same internal dimensions as the South Carolina series of tunnels but omitting one room; volume 2,900 ft^3.

Any further uncertainty as to whether detonations or deflagrations are being observed can be resolved by a pressure record. In figure 13, A shows a typical deflagration record in the Crawshaw-Jones apparatus; while several shocks are reflected from the ends of the tube, the average pressure clearly builds up over about 25 msec. In a typical detonation record (B, fig. 13) the first pressure pulse, corresponding to the detonation front, is the strongest and succeeding shocks are progressively weaker.

Wave velocities as function of concentration of propane-air, acetylene-air, and ethylene oxide-air mixtures, are given in tables 5, 6, and 7, respectively. The detonable ranges for the same three systems are shown in figures 14 through 16.

The limits of detonability for acetylene-air and propane-air mixtures initiated with 10 g of explosive are about equal to their reported flammability limits (table 8). The detonability limits for MAPP-air were somewhat wider than the reported flammability limits. The energy required to initiate a detonation is usually many orders of magnitude greater than that required to initiate a deflagration. The width of the detonable range depends on the

[25] Brochet, C., and N. Manson. Ondes Explosives et Detonations Instables dans les Mélanges Propane-Oxygène-Azote. Colloq. Intern. Centre Nat'l Rech. Sci. (Paris) 109, 1962, pp. 209-221.

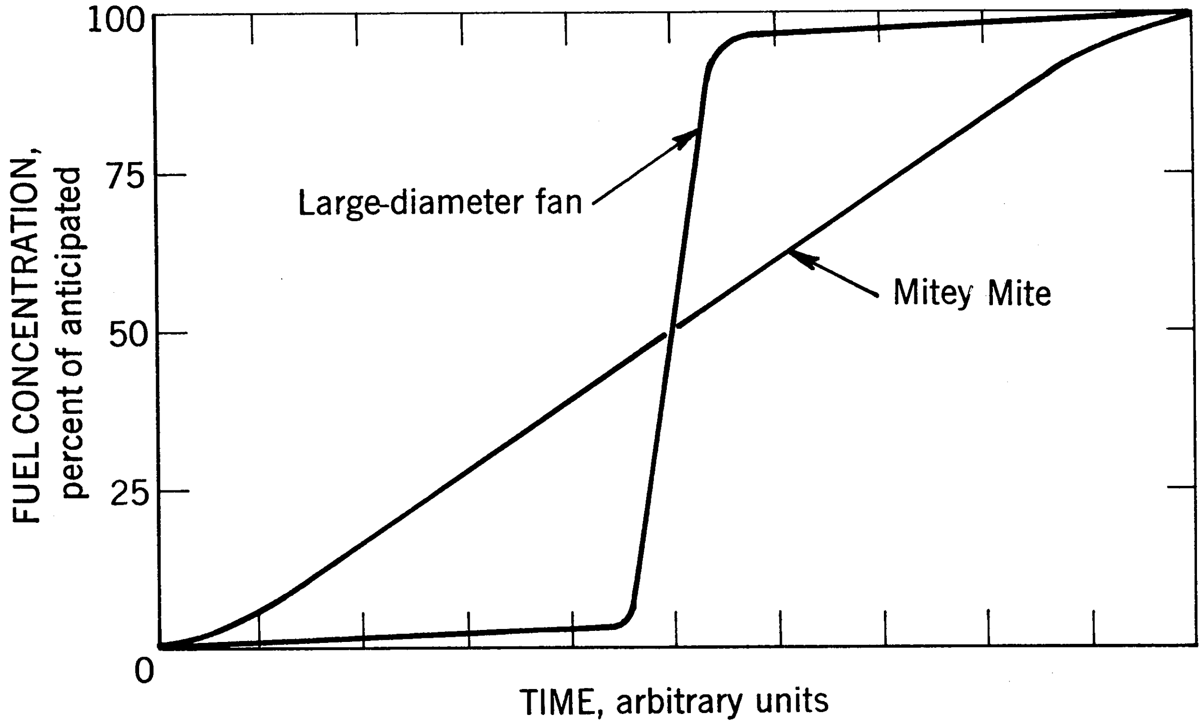

FIGURE 11. - Concentration as a Function of Time for Two Blower Systems at a Point in the Center of the 50-M Tunnel.

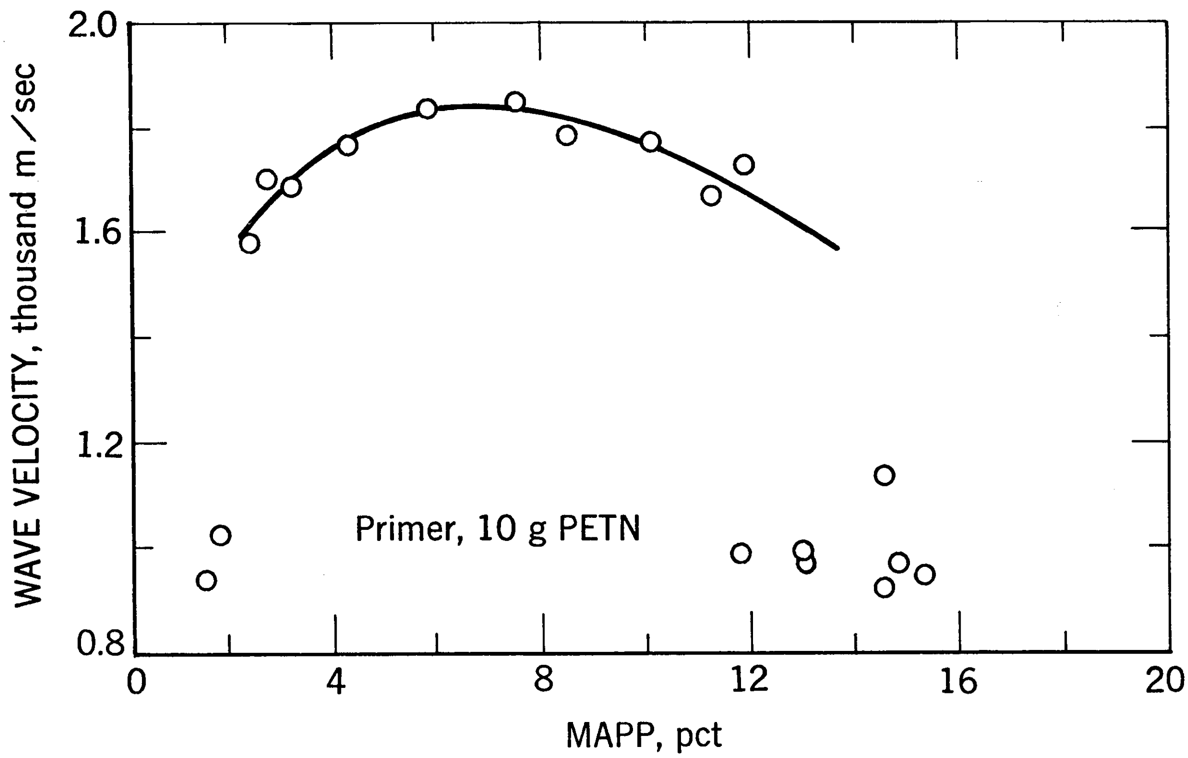

FIGURE 12. - Wave Velocity as a Function of Fuel Concentration for MAPP-Air Mixtures Initiated With 10 G of PETN in the Crawshaw-Jones Apparatus.

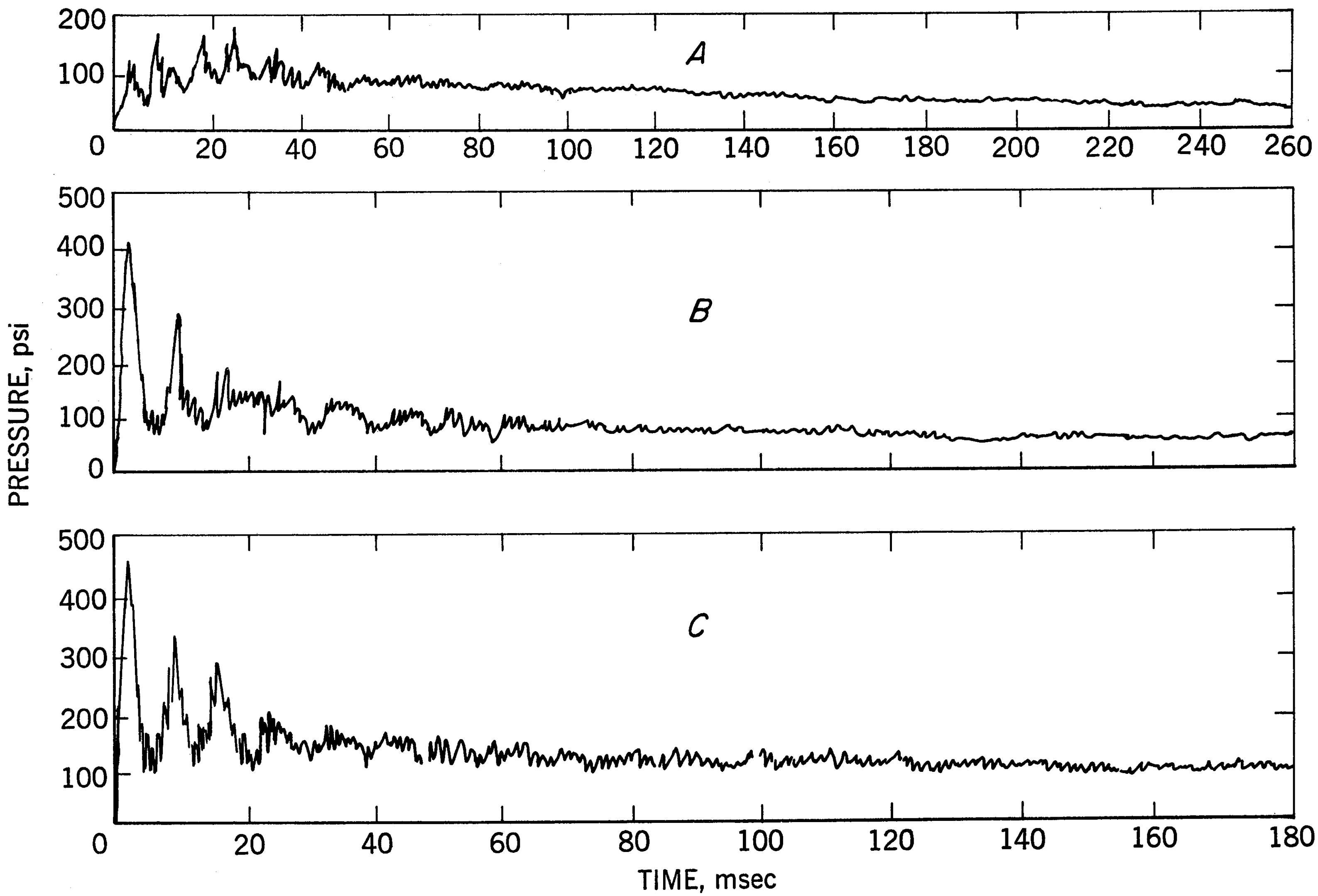

FIGURE 13. - Typical Closed-Chamber Pressure Records in the Crawshaw-Jones Apparatus for *(A)* MAPP-Air Deflagration; *(B)* MAPP-Air Detonation; and *(C)* MAPP-Air-Oxygen Detonation.

strength of the initiating source, as shown by the data obtained with MAPP where the limits are 4.1 and 7.6 pct for a 1-g primer, 2.4 and 13.7 pct for a 10-g primer, with an upper limit of at least 30 pct for a 100-g primer. Similarly, the upper limit of ethylene oxide is increased from 18 to >30 pct by increasing the booster size from 10 to 100 g.

TABLE 5. - Wave velocities and impulses in various propane-air mixtures initiated with 10 g of PETN in the Crawshaw-Jones apparatus

Propane, pct	Wave velocity, m/sec	Impulse, psi sec
2.0	990	-
2.1	960	12.99
2.2	1,370	16.00
2.3	1,060	15.85
2.3	1,070	15.34
2.4	1,360	-
3.0	1,660	18.25
3.9	1,820	18.33
5.0	1,820	16.13
5.8	1,890	16.21
6.7	1,820	14.45
7.8	1,700	-
8.3	1,610	10.82
9.2	1,470	11.68
9.4	960	10.20
9.9	900	7.58
10.2	900	5.92

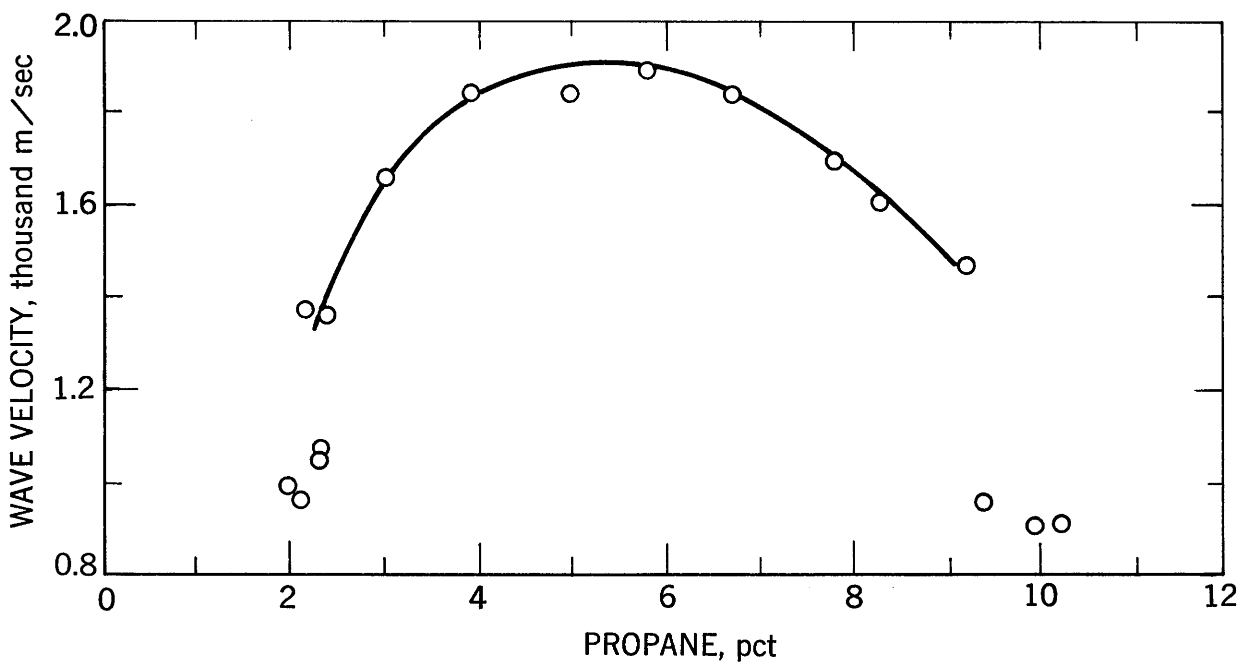

FIGURE 14. - Wave Velocity as a Function of Fuel Concentration for Propane-Air Mixtures Initiated With 10 G of PETN in the Crawshaw-Jones Apparatus.

TABLE 6. - Wave velocities and impulses for various acetylene-air mixtures initiated with 10 g of PETN in the Crawshaw-Jones apparatus

Acetylene, pct	Wave velocity, m/sec	Impulse, psi sec
2.5	980	7.32
3.0	990	10.46
3.9	1,560	11.32
4.5	1,660	12.21
6.0	1,830	17.38
10.9	1,970	17.42
18.9	2,110	16.20
20.2	1,970	17.35
26.7	-	16.56
38.7	2,010	16.95
39.9	-	17.42
55.7	1,970	16.90
69.0	-	18.74
77.0	1,943	21.78
100.0	1,870	32.20

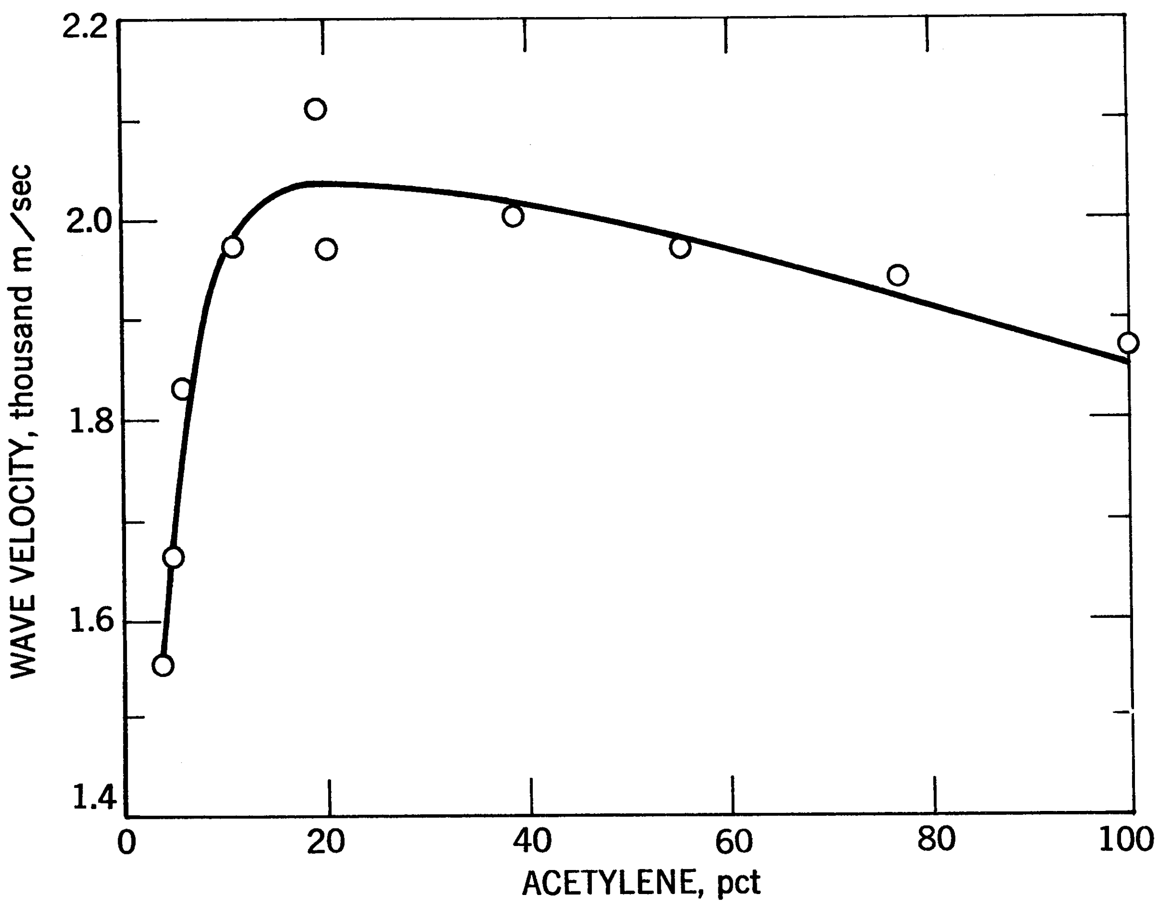

FIGURE 15. - Wave Velocity as a Function of Fuel Concentration for Acetylene-Air Mixtures Initiated With 10 G of PETN in the Crawshaw-Jones Apparatus.

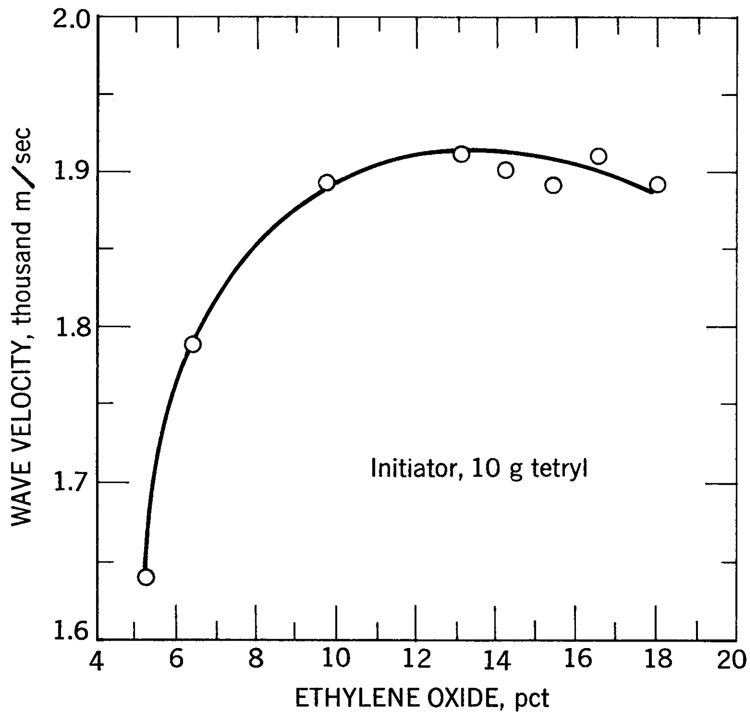

FIGURE 16. - Wave Velocity as a Function of Fuel Concentration for Ethylene Oxide-Air Mixtures Initiated With 10 G of Tetryl in the Crawshaw-Jones Apparatus.

TABLE 7. - Detonation velocities of various ethylene oxide-air mixtures in the Crawshaw-Jones apparatus

Primer	Concentration in air, pct	Average detonation velocity, m/sec
10 g tetryl	2.5	[1]F
	3.6	F
	5.3	1,640
	6.2	1,790
	9.8	1,890
	13.1	1,910
	15.3	1,890
	16.5	1,910
	18	1,890
	21.4	F
	22.7	F
	22.3	F
	27.5	F
	27.4	F
	29.2	F
100 g tetryl	20.7	2,350
	21.4	2,320
	21.8	2,290

[1]F: Failed to detonate.

TABLE 8. - Limits of detonability and of flammability

Mixture	Initiator	Detonability: Lower limit, pct	Detonability: Upper limit, pct	Flammability[1]: Lower limit, pct	Flammability[1]: Upper limit, pct
MAPP-air............	Spark.......	-	-	3.4	10.8
	1 g PETN....	4.1	7.6	-	-
	10 g PETN...	2.4	13.7	-	-
	100 g tetryl	-	[2]30	-	-
Acetylene-air........	Spark.......	-	-	2.5	100
	10 g PETN...	2.0	100	-	-
Propane-air..........	Spark.......	-	-	2.1	9.5
	10 g PETN...	2.2	9.2	-	-
Ethylene oxide-air...	Spark.......	-	-	3.0	100
	10 g tetryl.	5.3	18.0	-	-
	100 g tetryl	-	[2]30.0	-	-

[1]Hembree, J. D., R. W. Belfit, H. A. Reeves, and J. P. Baughman. A New Fuel Gas-Stabilized Methylacetylene-Propadiene. Welding J., May 1963, pp. 3-12.
[2]Higher concentrations were not tried.

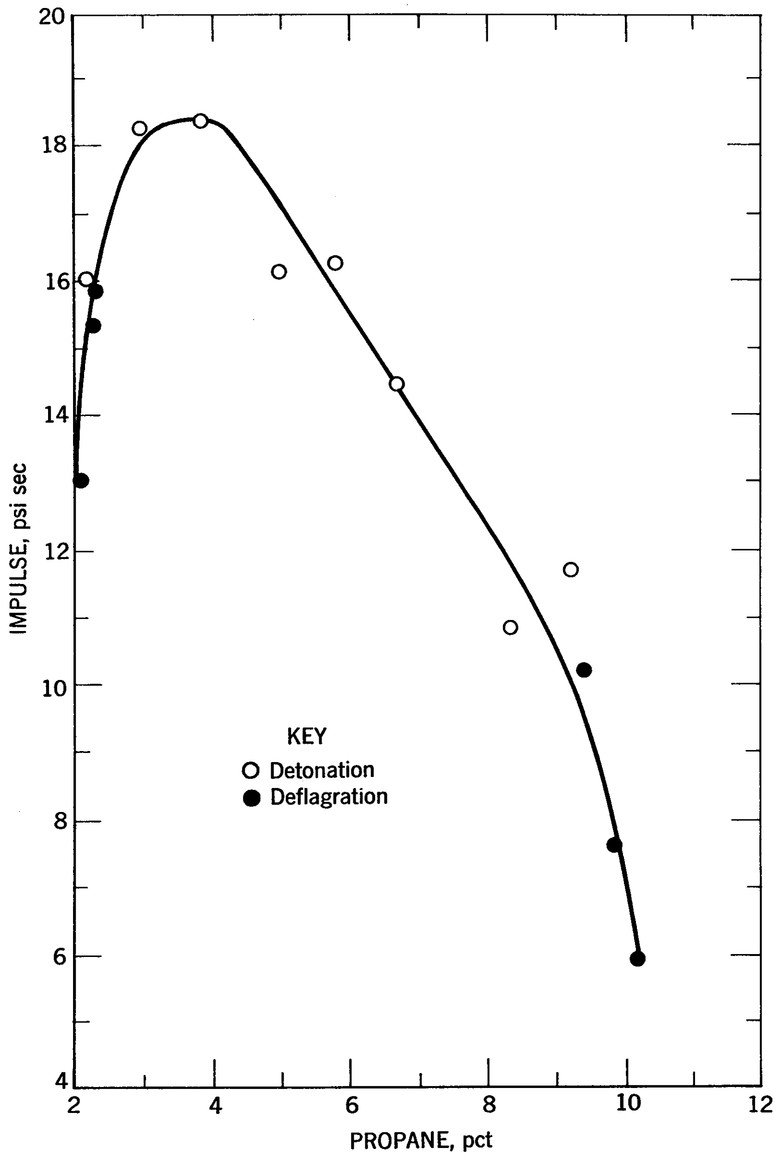

FIGURE 17. - Impulse as a Function of Fuel Concentration for Propane-Air Mixtures Initiated With 10 G of PETN in the Crawshaw-Jones Apparatus.

The numerous Crawshaw-Jones pressure records (fig. 13) also serve as a measure of the relative impulses of detonating mixtures in the special case of a nonyielding closed tunnel. Since there is no pressure relief in the Crawshaw-Jones except from the cooling of the product gases, the impulse (area under the pressure-time curve) had to be measured over some arbitrary period which we took to be 200 msec. The measured values are plotted against the concentration of propane, MAPP, and acetylene-air (figs. 17, 18, and 19). The propane-air curve has a narrow peak near stoichiometric, whereas MAPP-air gives a much broader maximum and acetylene-air gives a plateau extending to about 60 pct fuel, followed by a surprising upturn toward 100 pct fuel. It is also of interest that in each case the curve is fitted to data from deflagrating as well as detonating mixtures. Thus, if a chamber provides constant volume confinement, the side-on impulse depends primarily on the concentration of the gas mixture, regardless of whether detonation develops. In this connection, we made a careful extrapolation of a detonation record for 5 pct MAPP-air mixture to zero time. This should eliminate heat loss effects and give the pressure of a constant volume explosion, p_v or $p_m(o)$. The value found was 131 psig, from which 2 psig should be subtracted for the effect of the 1.1-g PETN primer. For comparison, our computed value of p_v for 5 pct methylacetylene is 127 psig. This is the best experimental check that we have of our computational program for explosion pressures.

Pressure Transients and Impulses (Steel Tunnel)

The experiments which offered the best control of all variables were conducted in the 2-ft-diam by 163-ft-long steel tunnel. Among them were two

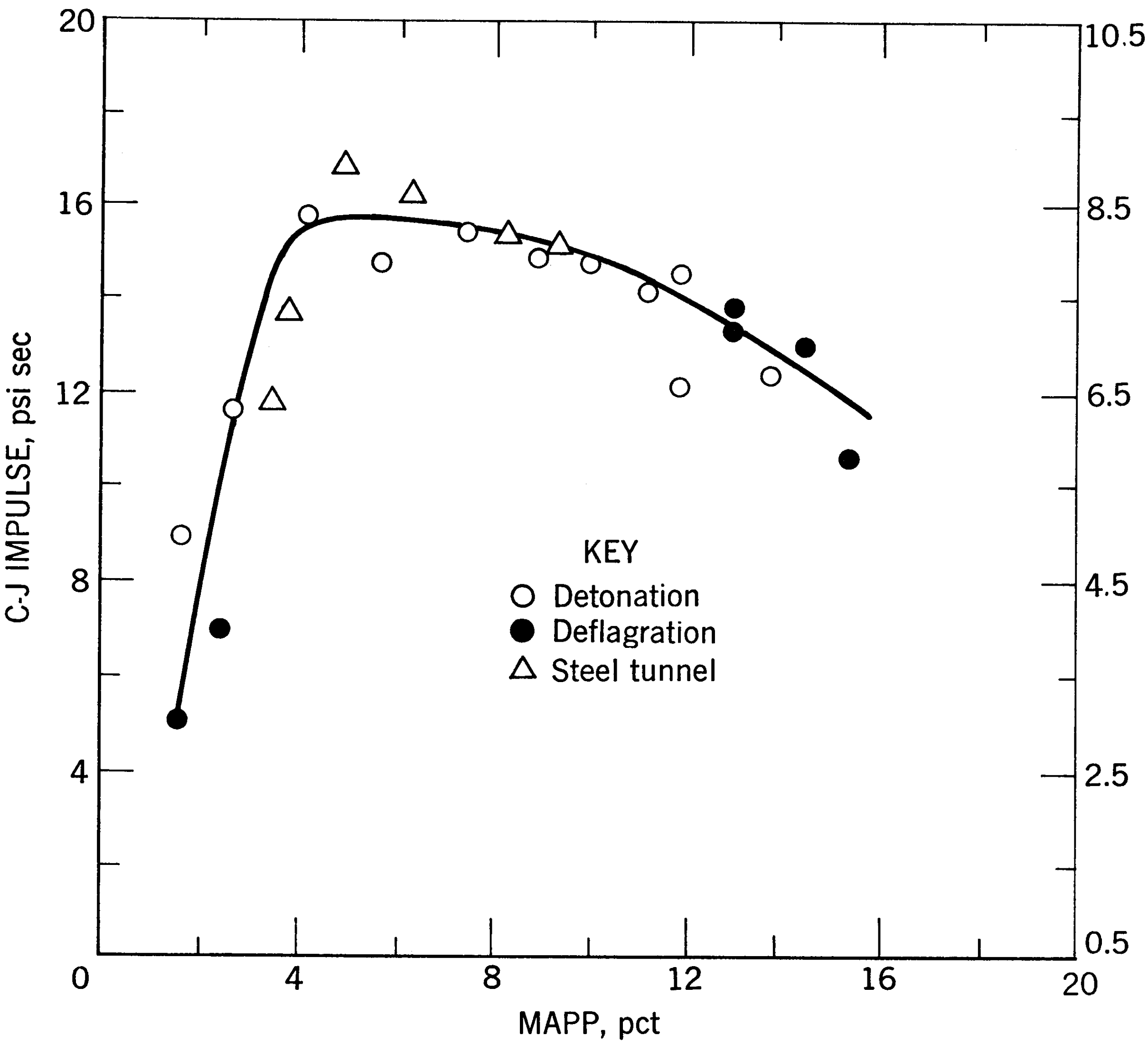

FIGURE 18. - Impulse as a Function of Fuel Concentration for MAPP-Air Mixtures. Circles represent detonations and deflagration initiated with 10 g of PETN in the Crawshaw-Jones apparatus; triangles represent detonations initiated with 100 g of tetryl in the 50-m steel tunnel.

series of MAPP-air and propane-air detonations which were conducted during warm weather (minimizing fuel vaporization problems) and utilizing our latest instrumentation; the resulting data (tables 9 and 10) provide an evaluation of the one-dimensional detonation model in a system of this unusual size. In comparable experiments with gasoline-air (table 11), the mixture composition was less well controlled. The experiments with acetylene-air (table 12) date from the earliest stage of the program when adequate instrumentation was lacking. Thus the data for gasoline and acetylene are of interest only in terms of the impulses obtained with these fuels relative to those from propane and MAPP.

TABLE 9. - Observations of MAPP-air detonations in 50-m steel tunnel with initiation end closed

Observation	Test	Instrument stations 1	2	3	4	5	Average
MAPP concentration, pct	136	3.4	3.5	3.4	3.3	3.2	3.4
	137	3.6	3.6	3.6	3.4	3.3	3.5
	148	4.6	5.1	4.9	4.7	5.1	4.9
	141	6.2	6.0	6.3	6.0	5.8	6.1
	175	7.5	8.1	7.9	9.3	7.4	8.0
	134	8.9	8.7	8.7	8.5	8.7	8.7
Peak pressure, psig....	136	186	300	-	258	-	248
	137	217	[1] (310)	[1] (209)	268	[1] (230)	243
	148	216	-	-	294	-	255
	141	233	300	-	289	-	274
	175	[1] (210)	270	222	-	[1] (236)	246
	134	249	300	238	311	-	275
Wave thickness, msec...	136	5	7	13	21	-	-
	137	[1] 6	[1] 10	[1] 17	-	[1] 20	-
	148	5	10	14	18	-	-
	141	5	10	14	20	-	-
	175	5	9	14	20	22	-
	134	5	9	15	20	[1] 21	-
Average...........		5	9	14	20	22	-
Predicted.........		4	8	11	15	19	-
Plateau pressure, psig.	136	88	79	-	75	-	81
	137	88	-	-	89	-	89
	148	105	100	-	104	-	103
	141	109	86	-	99	-	98
	175	75	90	70	-	-	78
	134	103	107	96	91	-	99
Plateau duration, msec.	136	71	54	35	12	2	-
	137	[1] 71	[1] 54	[1] 34	-	[1] 2	-
	148	58	46	32	15	-	-
	141	64	49	35	14	-	-
	175	66	48	34	14	-	-
	134	64	52	33	14	-	-
Average...........		65	50	34	14	2	-
Impulse, psig..........	136	7.8	5.9	-	4.8	-	6.2
	137	8.1	-	-	6.5	-	7.3
	148	11.1	7.5	-	8.0	-	8.9
	141	9.7	8.0	-	7.1	-	8.3
	175	9.2	9.1	5.7	-	[1] (5.4)	8.0
	134	8.2	8.7	7.6	6.6	-	7.8

[1] Readings from other experiments of the same nominal concentration.

TABLE 10. - Observations of propane-air detonations in 50-m steel tunnel with initiation end closed

Observed parameter	Test	Instrument stations					Average
		1	2	3	4	5	
Propane concentration, pct	158	5.2	3.2	5.2	5.1	5.1	4.8
	166	2.6	5.0	5.2	5.2	5.2	4.6
	160	6.3	6.1	6.4	6.3	6.3	6.3
	169	6.3	6.1	6.6	6.6	6.6	6.4
	170	6.5	6.7	6.2	6.4	6.1	6.4
	171	8.4	8.4	8.4	8.4	8.1	8.3
Peak pressure, psig.......	158	176	-	193	-	-	219
	166	155	229	328	209	227	
	160	207	-	190	-	170	
	169	176	-	-	209	221	210
	170	-	-	283	-	221	
	171	-	-	238	-	204	221
Average..............		179	229	246	209	209	-
Wave width, msec..........	158	3	-	16	-	26	-
	166	6	10	14	20	26	-
	160	5	-	10	-	18	-
	169	4	-	-	23	-	-
	170	4	-	14	20	-	-
	171	4	-	13	17	18	-
Average..............		4	10	13	20	22	-
Plateau pressure, psig....	158	83	-	85	-	-	84
	166	83	86	91	75	-	84
	160	83	-	86	-	91	85
	169	78	-	-	75	-	77
	170	-	-	85	-	-	85
	171	-	-	79	-	85	79
Plateau duration, msec....	158	[1] (41)	-	[1] (33)	-	-	-
	166	71	60	46	33	-	-
	160	76	-	37	-	-	-
	169	80	63	-	35	-	-
	170	78	62	46	-	-	-
	171	77	63	50	37	-	-
Average..............		76	62	45	35	-	-
Predicted............		84	68	52	35	19	-
Impulse, psi sec..........	158	8.2	-	5.0	-	-	-
	166	9.3	9.0	9.4	6.9	6.9	-
	160	7.9	-	6.4	-	5.3	-
	169	10.2	-	-	6.2	7.6	-
	170	-	-	9.5	-	6.7	-
	171	-	-	7.6	-	3.5	-
Average..............		8.9	[1] (9.0)	7.6	6.6	6.0	-

[1] Values omitted from calculation of averages.

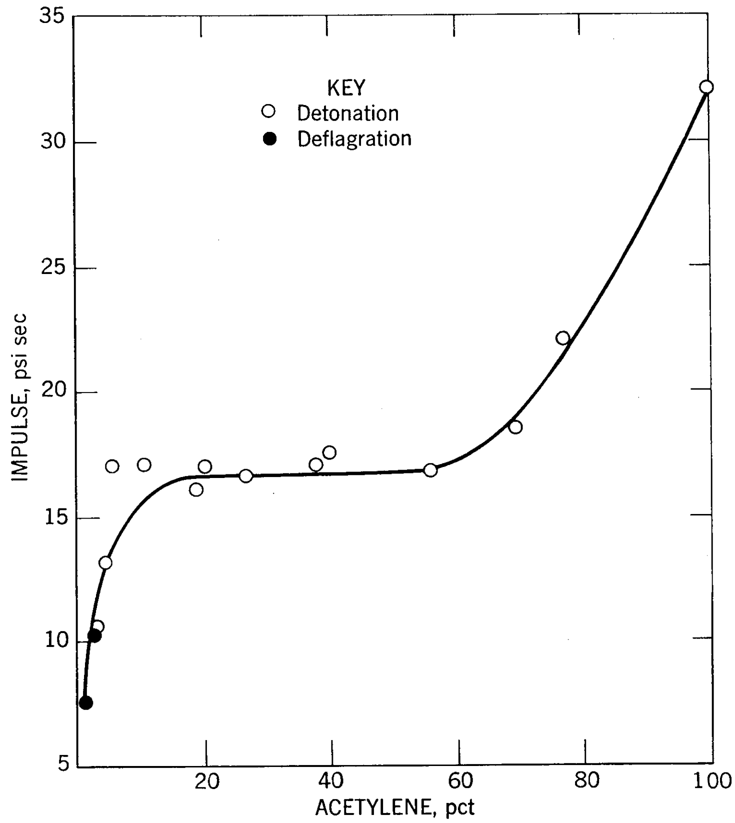

FIGURE 19. - Impulse as a Function of Fuel Concentration for Acetylene-Air Mixtures Initiated With 10 G of PETN in the Crawshaw-Jones Apparatus.

TABLE 11. - Impulses of gasoline-air detonations in steel tunnel with initiation end closed

Test	Impulse at instrument stations, psi sec				
	1	2	3	4	5
194	9.7	-	4.3	3.6	7.1
196	10.8	-	6.7	8.3	5.1
197	10.7	-	9.1	7.6	6.4

MAPP and propane concentrations prior to firing are listed in tables 9 and 10. Measurements obtained from five pressure transients are also listed. The five transients from a propane-air test (fig. 20) are generally representative for all mixtures in the steel tunnel. These transients may be compared with the model curve of figure 1. As the instrument stations were spaced at 26.5-ft intervals, the slope of the dashed line connecting points B of figure 20 indicates a detonation velocity of 1,850 m/sec in a 4.6-pct propane-air mixture; this is as nearly accurate as the measurement of time interval. In the same way, the line connecting points E of figure 20 should indicate sound velocity in the burned gas; the value obtained, 875 m/sec, is sufficiently inaccurate to show that we are not dealing with an ideal detonation; the reason for this low value of sound velocity will become apparent below.

TABLE 12. - Impulses at downstream end of steel tunnel with both ends open

Fuel	Average concentration, pct	Impulse at station 5, psi sec	Fuel	Average concentration, pct	Impulse at station 5, psi sec
Acetylene	5.3	2.5	MAPP.....	4.5	3.4
	7.1	3.0		5.8	3.3
	8.4	3.9		6.0	3.3
	~12	3.3		6.6	4.2
	~19	2.7		7.9	2.2
				8.6	3.5
				8.9	2.6

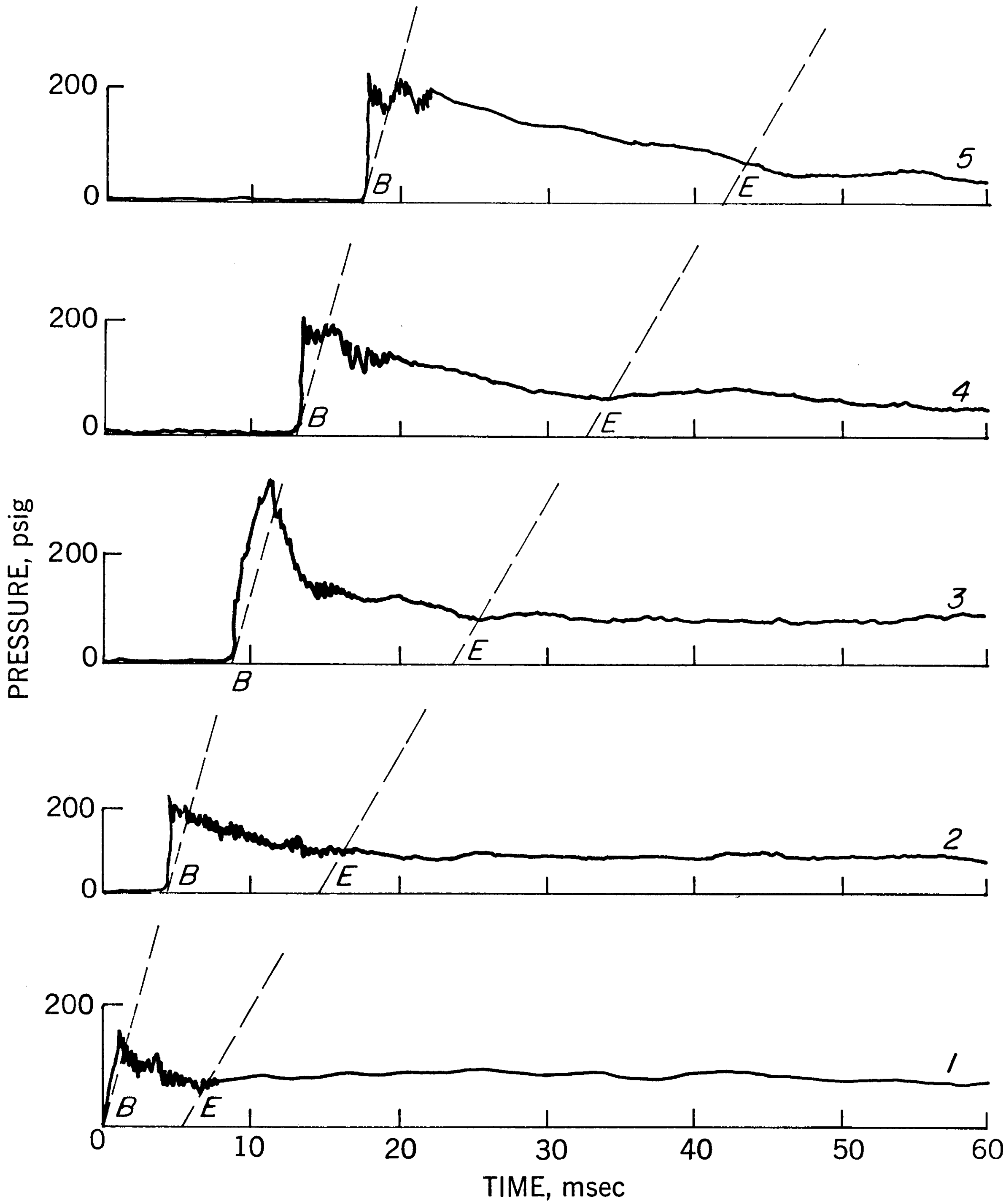

FIGURE 20. - Pressure-Time Transients at Five Instrument Stations in 50-M Steel Tunnel for a 4.6-Pct Propane-Air Shot (Test 166).

Peak (C-J) pressures are listed in tables 9 and 10 although data were omitted whenever the pressure transducer appeared sensitive to "ringing" of the steel tube; the peak pressures are too erratic for any real test of the detonation model. Figure 21 compares the experimental values for MAPP-air mixtures (circles) with the Zeldovich approximation for C-J pressure (labeled $p_2 = 2\ p_v$). To reduce the scatter of data with propane-air mixtures, we have averaged peak pressures of tests 160, 169, and 170, and of tests 158 and 166

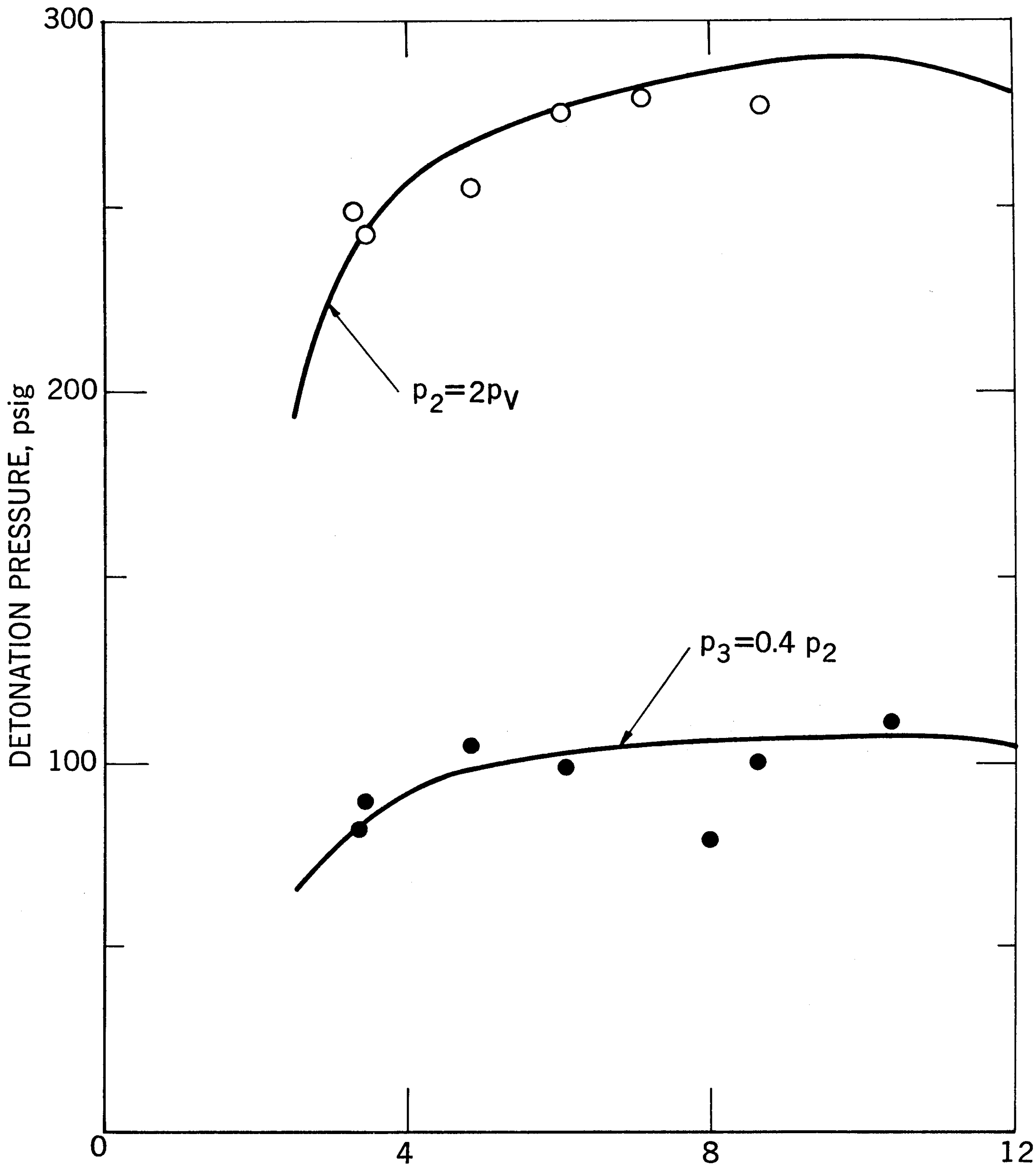

FIGURE 21. - Computed and Experimental Pressures in MAPP-Air Detonations. Upper curve (C-J plane), lower curve (plateau), and circles (experimental).

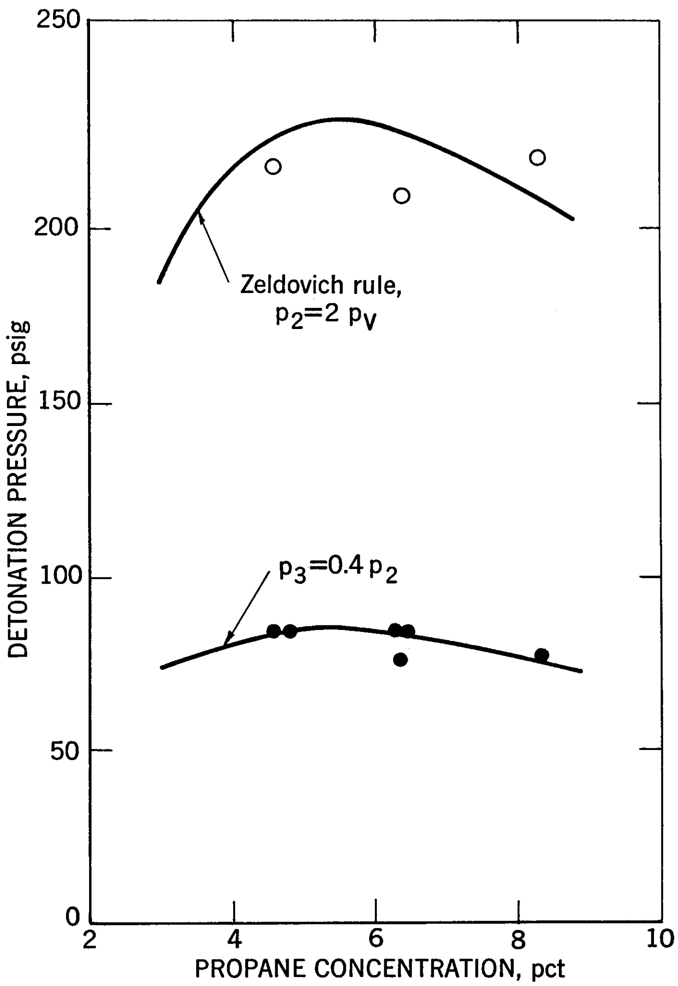

FIGURE 22. - Computed and Experimental Pressures in Propane-Air Mixtures. Upper curve (C-J plane), lower curve (plateau) and circles (experimental).

which involved the same mixture concentrations. The averaged results are shown in figure 22 for comparison with 2 p_v. About all one can say is that computed pressures are lower with propane-air than with MAPP-air mixtures and that experiments do bear this out.

A test of the Taylor expansion hypothesis--that is, of the rate of pressure drop behind the C-J plane--is obtained by measuring the time intervals BE in figure 20. Experimental numbers are given in the "wave thickness" section of tables 9 and 10. In table 9, the observed values are averaged at each instrumentation point for comparison with predicted values. While the differences are small, the pressure pulse is clearly wider than expected at all stations and this ties together with the low value of sound velocity noted above.

Whatever the failures of the one-dimensional model at the wave front or in the expanding gases, it does give a good estimate of pressure in the static gas zone. To obtain the lower curves of figures 21 and 22, plateau pressures were calculated by equations 14 through 18 for $\gamma = 1.17$. The experimental points (averaged values from the plateau pressures in tables 9 and 10) are sprinkled closely about the predicted curves.

The duration of the plateau (interval EH, fig. 1) is shown in table 9 to be a mild function of concentration, being longest in very lean mixtures where the gas temperature and sound velocity are lowest. This is a contributing factor to the relatively high impulses which will be discussed below for lean mixtures. Also, the durations of propane-air plateaus (table 10) are significantly longer than for MAPP-air. This, too, is a compensating factor which opposes the lower pressures in propane-air as compared with MAPP-air. In the background section we assumed that the duration of a plateau is given by the time for point E (fig. 20) to move at 54 pct of detonation velocity to the open end of the tunnel and for a rarefaction to return at sonic velocity to the pressure station. The predicted durations are given in the last row of the plateau duration section of table 10, for comparison with experimental values. The measured values are clearly shorter, which suggests that the aerodynamics of the pressure pulse as it reaches the tunnel opening are not as straightforward as assumed.

Impulses for MAPP-air are listed in table 9, and averaged values are shown as a function of concentration in figure 18 along with Crawshaw-Jones data (note, however, the difference in scale of ordinate). The high impulses in lean mixtures are strikingly evident.

The average of 17 impulses with propane-air (table 10) was 7.4 psi sec, while the average of 20 values with MAPP-air (table 9) was 7.7 psi sec. In general, pressures were higher with MAPP, but this was nearly compensated by longer durations of plateau with propane.

In three tests conducted with gasoline-air for comparison with propane and MAPP (table 11), fuel concentrations were uncertain because of incomplete vaporization. In test 194 the gasoline was not preheated and the fuel mixture was presumably the leanest. In tests 196 and 197, the gasoline was preheated to give nearly complete vaporization at the tunnel entrance although there may have been subsequent condensation on the tunnel walls. Impulses in the three tests average 7.5 psi sec over the 12 measured values. Again there seems to be little to choose among hydrocarbons on this performance criterion.

Table 12 lists impulses at instrument station 5 (near the downstream end of the steel tunnel) for acetylene-air and MAPP-air detonations. The initiation end of the tunnel was open in each case, which explains why the impulses were lower than in tables 9 through 11. With acetylene-air, a maximum value of 3.9 psi sec was obtained with a slightly rich mixture (8.4 pct as compared with stoichiometric 7.75 pct). The decline of impulse at higher concentrations was recognized as departing from prediction (see table 2) and was attributed to the soot which formed at 12 pct acetylene and higher. MAPP-air gives about the same range of values over a somewhat narrower range of concentrations, again indicating that all hydrocarbon-air systems give about the same impulse.

A typical transient from the above series of tests is given as D in figure 23. Comparison with curve B of the same figure shows the effect of end closure on impulse at the downstream end of the tunnel.

Effect of Oxygen Enrichment on Impulse

The first experimental evaluation of oxygen enrichment was made in the South Carolina tunnel tests (table 13). The first three tests involved acetylene-air at unknown fuel concentration. Oxygen concentrations would surely have been 19 to 20 pct throughout and impulses ranged from an average of 3.3 psi sec in test 1 to an average of 3.9 psi sec in test 3. The aluminum used in test 3 was certainly not well distributed and can be disregarded. Tests 6 and 7 involved 26 to 29 pct oxygen and the change from acetylene to MAPP can be ignored. Impulses increased in roughly the same proportion as oxygen concentration in general accord with figure 6. Extrapolation of the trend of figure 6 indicates that further increases of oxygen would give diminishing returns in pressure and impulse.

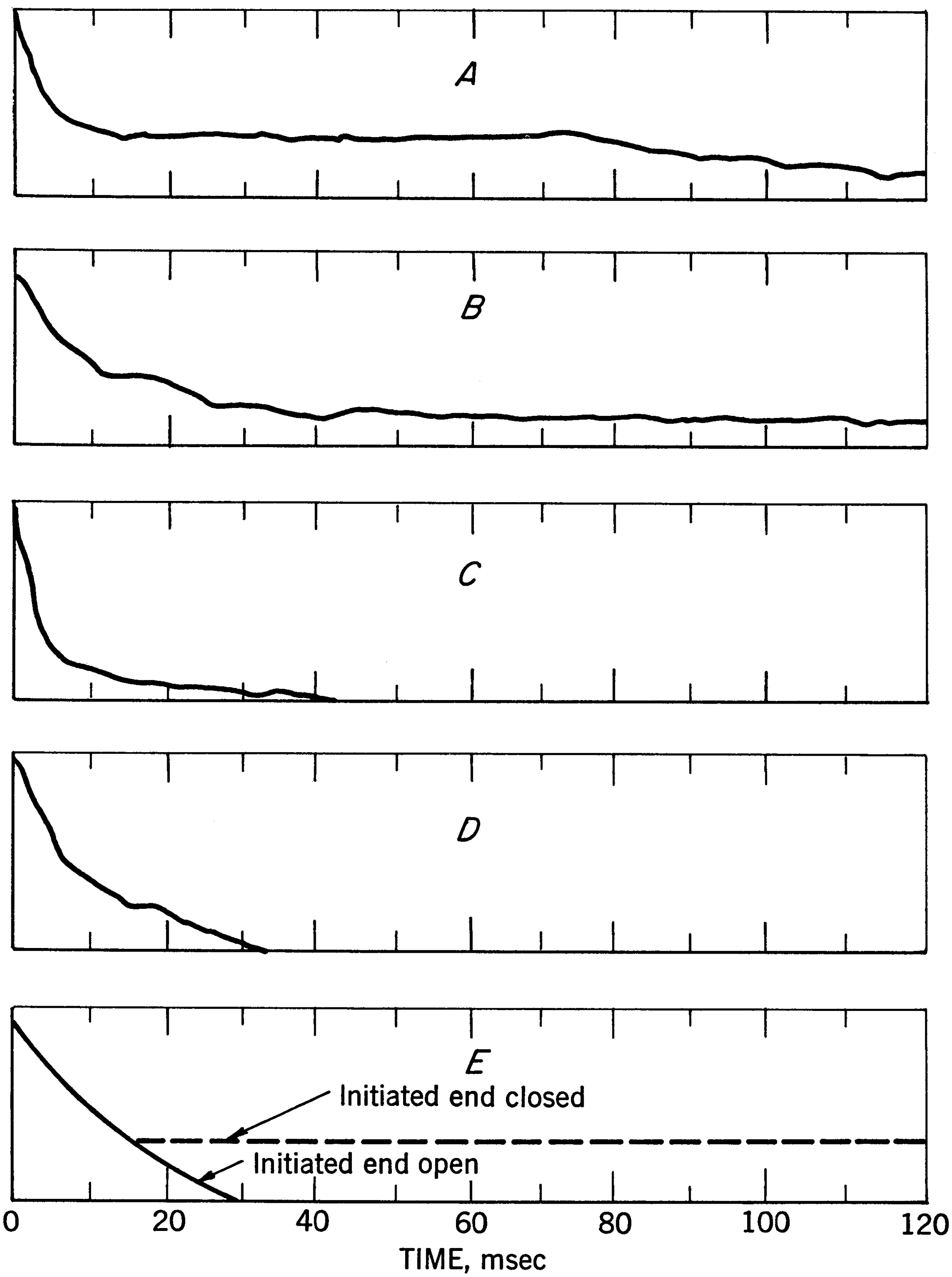

FIGURE 23. - Typical Pressure Profiles at Various Positions in 50-M Tunnel. *A,* The initiation end when closed; *B,* the downstream end when initiation end is closed; *C,* initiation end when open; *D,* downstream end when initiation end is open; and *E,* the theoretically predicted profile for open and closed initiation end as reviewed at 80 ft from initiation end.

TABLE 13. - Condensed summary of results at Clark Hill Reservoir, S.C.

Test	Propellants	Concentrations, pct	Depth of tunnel, ft		Impulse, psi sec
			Destroyed	Damaged	
1	C_2H_2-air.....	Unknown.......	5	8	2.8-3.8
2	C_2H_2-air.....	......do......	5	8	3.5-4.3
3	C_2H_2-air-Al..	......do......	5	8	3.3-4.6
4	MAPP-air.....	3 MAPP........	-	7	4.8-6.3
5	MAPP-air-O_2..	2.5- 5.1 MAPP 21.9-24.4 O_2..	8	10	2.7-6.5
6	MAPP-air-O_2..	6.9-10.3 MAPP 27.3-28.8 O_2..	-	[1]10	5.4,9.8,3.7
7	MAPP-air-O_2..	9.2- 9.7 MAPP 26.2-26.3 O_2..	-	[2]8	5.4,5.6

[1]As supplied by Waterways Experiment Station or as integrated from copies of WES pressure-time record.

[2]Tunnels in tougher overburden than tunnels 1 through 5.

Surprising results were encountered in tests 4 and 5. Tunnel 4 was loaded on an impromptu basis after the failure of an ether mixture to detonate and was not equipped for gas sampling; however, it could not have contained more than about 3 pct MAPP in air. Nonetheless impulses were comparable to those of tunnels 6 and 7. Tunnel 5 was also shot with an extremely lean mixture and gave the most spectacular destruction of the series. No explanation for this unexpected performance is forthcoming from figure 6 or from any of our thermodynamic computations. Excess oxygen is almost indistinguishable in its effect on computed pressures and temperatures from the nitrogen that it replaces.

In the following experiments with oxygen enrichment we have concentrated less on the performance of fuel-balanced mixtures, which follows a straightforward and expected trend, than on the special behavior of lean mixtures.

Small-Scale Tests

In nine tests in the Crawshaw-Jones apparatus (table 14) the objective in each case was to fill the 93-1 apparatus with a 5.0-pct MAPP mixture, with or without a supplemental 5 pct of oxygen. Without supplemental oxygen the mixture is stoichiometric for burning methylacetylene and propadiene to CO_2 and H_2O; with the added oxygen, it should be fuel lean as in tunnel 5 in South Carolina.

To minimize reaction with fuel-rich combustion products from the primer, especially in the presence of supplemental oxygen, a 1.1-g PETN pellet was used as initiator instead of the usual 10-g tetryl charge, the oxygen balance of PETN being -10 pct as compared to -47 pct for tetryl. Even with this precaution, oxygen-enriched mixtures were appreciably more energetic than the simple fuel-air mixtures. The impulses ranged from 15.74 to 17.67 psi sec for the nearly stoichiometric mixtures and from 17.71 to 22.30 psi sec for the oxygen-rich mixtures. Tracings for representative pressure transients

(B and C, fig. 13) suggest that the impulse of stoichiometric MAPP-air can be increased on an average of about 20 pct by adding about 5 pct oxygen to the mixture.

TABLE 14. - Impulses and detonation velocities in the Crawshaw-Jones apparatus with and without oxygen enrichment

Shot No.[1]	MAPP, pct	Supplemental oxygen, pct	Impulse, psi sec	D, m/sec
1	4.8	-	15.74	1,600
2	4.8	-	17.67	1,670
3	4.7	-	16.97	1,900
4	5.7	-	16.35	1,880
5	5.2	-	16.79	850
6	5.0	5.0	19.24	2,040
7	5.1	5.5	22.35	1,890
8	5.1	5.9	21.70	1,890
9	4.7	4.9	17.71	1,870

[1] Primer used: 1.1-g PETN pellet.

Part of the additional energy is attributable to the presence of a small amount of carbonaceous material extraneous to both the gaseous fuel and primer. In test 7, which yielded the highest impulse, the carbon input including the primer was 7.20 g, whereas 7.49 g carbon were found in the combustion products, the amount of unaccountable carbon being 0.29 g. This small amount of additional carbon does not explain the 20-pct higher impulse, but because of the uncertainties associated with small apparatus, the study was continued in the 500-ft^3 steel tunnel.

Steel Tunnel Tests with Supplemental Oxygen

On this scale, any extra carbon from a booster must be negligible but it is always uncertain that the side wall of the chamber is perfectly clean. Accordingly, we adopted the procedure of a cleanout shot; that is, the detonation of a very oxygen-rich mixture to remove any carbonaceous residues on the wall prior to a data-producing test.

Results of five MAPP-air-oxygen tests are summarized in table 15. The first four tests (152, 146, 147, and 153) may be regarded as a series in which oxygen is held constant at 32 pct while MAPP is varied from 5.1 to 7.1 pct (8 pct is stoichiometric). The peak pressures were not very informative and are omitted for simplification of the table, but the plateau pressures are significantly higher than in air mixtures and the impulses are impressive. Within the validity of the data, there is no apparent trend of these impulses as one progresses from very fuel lean to almost stoichiometric.

In the final test of the series (176), there was too little oxygen for a continuation of the trend to appear. However, tests 178 and 187 were conducted with slightly rich propane mixtures at about the same oxygen concentration as above. In test 178 the impulse falls off drastically except at instrument position 1 where the propane concentration was accidentally low. In test 187 the mixture is rich throughout the tunnel and the one high impulse at instrument station 2 appears spurious.

TABLE 15. - Observations of hydrocarbon-air-oxygen detonations in steel tunnel with initiation end closed

Observation	Test	Instrument stations					Average
		1	2	3	4	5	
MAPP, pct	152	5.1	5.1	5.4	5.0	5.0	5.1
Oxygen, pct		32.0	32.6	32.7	32.8	32.6	32.5
MAPP, pct	146	5.5	5.4	5.4	5.8	5.4	5.5
Oxygen, pct		31.9	31.9	31.9	32.2	32.1	32.0
MAPP, pct	147	6.1	6.1	6.3	6.1	6.2	6.2
Oxygen, pct		31.1	31.1	31.7	31.5	31.8	31.4
MAPP, pct	153	7.8	7.3	6.9	6.2	7.1	7.1
Oxygen, pct		31.4	32.3	31.6	31.1	32.6	32.0
MAPP, pct	176	13.0	12.8	13.6	13.7	13.7	13.4
Oxygen, pct		27.2	27.0	27.4	27.3	27.2	27.2
Propane, pct	178	4.4	9.3	9.7	9.6	9.6	8.5
Oxygen, pct		32.4	30.8	31.3	31.0	31.2	31.4
Propane, pct	187	9.7	9.5	9.8	9.6	9.7	9.7
Oxygen, pct		30.9	30.4	30.5	30.6	30.7	30.6
Acetylene, pct	199	28.8	22.0	18.5	14.4	16.4	20.0
Oxygen, pct		49.7	36.7	31.2	26.8	29.0	34.7
Plateau pressure, psig	152	109	100	-	107	-	-
	146	124	-	-	-	-	-
	147	119	114	-	102	-	-
	153	-	100	118	103	-	-
	176	100	135	88	75	-	-
Impulse, psi sec	152	12.6	12.0	-	7.4	11.6	-
	146	13.0	-	-	-	-	-
	147	11.9	11.7	-	7.9	-	-
	153	-	-	11.9	-	13.0	-
	176	10.7	12.5	7.2	5.4	5.6	-
	178	12.3	-	5.7	-	5.3	-
	187	7.5	12.2	6.7	6.1	5.6	-
	199	13.3	12.4	9.7	-	10.2	-

The "hottest" mixture tried in the steel tunnel was a rich acetylene-oxygen mixture (test 199). Concentrations were less homogeneous than in other tests of the series but the $O_2:C_2H_2$ ratio was close to 1.75:1 throughout, corresponding to a product composition of about $CO_2 + 3\ CO + 2\ H_2O$. The impulses were no more impressive than with the lean mixtures involving augmented oxygen.

Effects of End Closure and of Initiation Point

In table 12 the average of 12 impulses at instrument station 5 is 3.2 psi sec; in tables 9, 10, and 11, the average of 9 impulses at the same position is 6.0 psi sec. This shows the effect of closing the upstream (initiation) end of the tunnel. At other positions in the tunnel, the difference is even more dramatic as one can see by inspecting transients A and C and transients B and D in figure 23.

In actual practice one does not often encounter the same permanent-type closure of a chamber that one achieves by bolting an end plate on a steel tunnel. The end closure is usually the weakest part of the overall structure. To simulate this temporary closure, we made nine tests in which each end of the steel tunnel was plugged with three sandbags, leaving perhaps one-third of the cross section open (table 16).

TABLE 16. - Observations of MAPP-air detonations in 50-m tunnel with sandbag closure at both ends

(MAPP concentration constant, point of initiation varied)

Observation	Tests	Initiation point	Instrument stations 1	2	3	4	5
Concentrations, pct MAPP	100	-	5.2	6.8	7.4	7.3	7.5
	101	-	-	-	-	-	-
	103	-	7.4	7.3	7.2	7.4	7.5
	104	-	7.2	6.8	6.9	7.1	6.8
	105	-	-	-	-	-	-
	106	-	6.7	7.4	7.4	7.2	7.1
	107	-	7.4	7.3	7.2	7.0	6.0
	108	-	7.8	7.5	8.0	7.9	8.0
	109	-	7.1	7.0	7.1	7.1	6.8
Peak pressures, psig....	100	End......	282	216	-	-	-
	101	Both ends	273	244	-	-	203
	103	Middle...	291	194	-	-	308
	104	End......	281	209	-	-	340
	105	Both ends	273	237	-	326	216
	106	Middle...	273	-	-	170	200
	107	End......	264	247	-	267	-
	108	Both ends	278	225	408	252	-
	109	Middle...	281	225	-	267	-
Average...........			278	225	-	256	253
Impulses (average) of 3 measurements, psi sec.	100,104,107	End......	9.0	4.1	-	5.4	-
	103,106,109	Middle...	11.4	4.2	-	5.2	-
	101,105,108	Both ends	6.8	5.1	-	6.1	6.1

An attempt was made to maintain a constant fuel concentration of about 7.2 percent MAPP, throughout. Our degree of success can be judged from table 16. The variable that was not well-controlled was the instant at which the sandbags left the mouth of the tunnel.

Three shots were made with initiation at one end of the tunnel, three with initiation at the longitudinal midpoint, and three with simultaneous initiations at the two ends. The averaged resulting impulses (table 16) show no particular trend as a function of initiation point. The average of all impulses in the nine tests was 6.34 psi sec which compares with 7.7 psi sec for the same fuel with end initiation and one permanent end closure.

A point of incidental interest in table 16 is the peak pressure measured at station 1. This was the most reliable instrumentation channel at the time and gave an averaged peak pressure of 278 psig with average deviation of 6 psig. The average value is plotted at 7.2 pct fuel in figure 21 and represents our best verification of any computed C-J pressure.

Comparison of Gaseous and Condensed Explosives

Gaseous and condensed explosives were compared in terms of the impulse attainable for equivalent loading of the tunnel. In the initial experiments we used Primacord which is composed of a PETN core covered with plastic sheathing (table 17). The cord was strung along the axis of the steel tunnel and initiated at the closed end. As in the gas explosions, pressures were recorded at five stations and representative transients were compared with gas detonation transients (fig. 24).

TABLE 17. - Impulses and plateau pressures obtained with Primacord strung axially through steel tunnel with initiation end closed

Test	PETN, g/ft	Sheathing, g/ft	Atmosphere	Impulse at instrument stations, psi sec					Plateau pressure, psig[1]
				1	2	3	4	5	
173	3.2	4.2	Air.......	9.3	7.3	7.0	4.3	4.9	82
174	6.7	8.1	....do....	-	11.6	8.5	5.7	5.0	105
155	10.5	7.9	....do....	-	6.6	9.2	5.1	5.1	107
157	10.5	7.9	....do....	9.1	-	7.5	4.8	-	139
156	21.0	15.8	....do....	-	-	9.8	-	-	150
188	5.5	4.5	Nitrogen..	1.6	3.6	1.3	1.0	.3	21
190	26.0	6.9	....do....	14.7	-	-	-	3.1	[2]91

[1]As measured at station 1. [2]Average of readings at stations 1 and 5.

When the PETN loading was varied from 3.2 to 21 g per foot of tunnel, the impulses stayed remarkably constant and about equal to the impulses of hydrocarbon-air mixtures, for example, of 8 g MAPP and 110 g air per foot of tunnel. Two tests were then made after purging the tunnel with nitrogen to evaluate the impulse that came from combustion of the plastic sheathing. If test 188 is compared with tests 173 and 174, one observes that replacing air with nitrogen reduces the impulse to about 20 pct. As only 9 g of sheathing can be burned stoichiometrically by the air in the tunnel, further increases

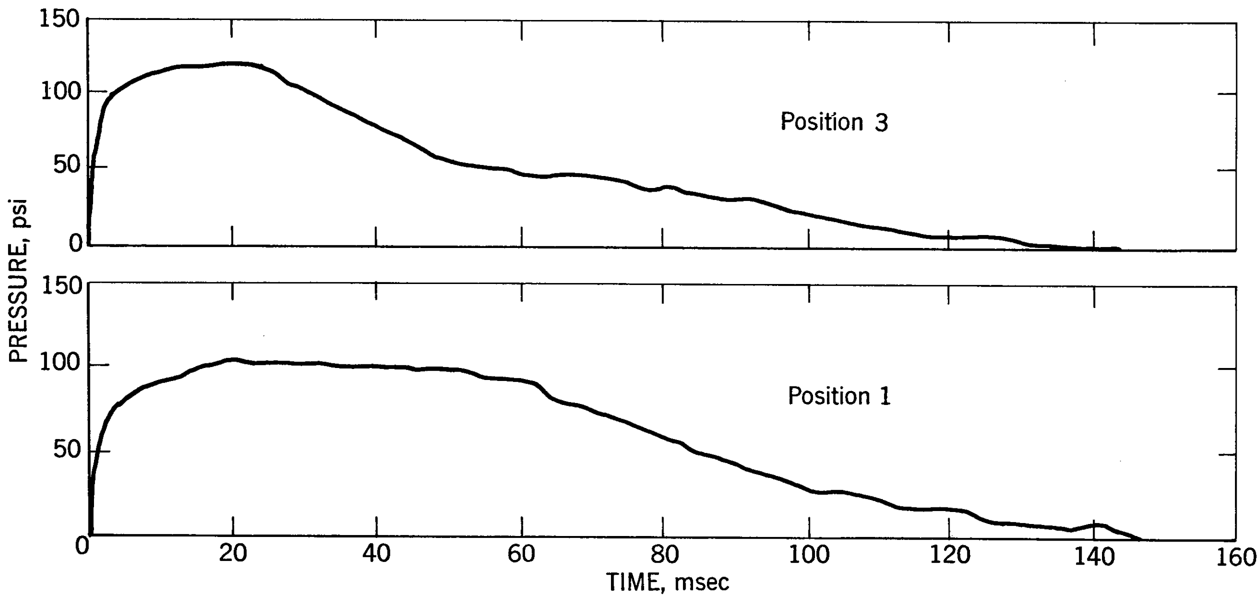

FIGURE 24. - Typical Pressure Records in the 50-M Steel Tunnel for 10.5-G/Ft Detonating Cord With the Initiation End Closed. Position 1 is at the closed end and position 3 is midway on the tunnel.

of the PETN-plastic loading (test 156) give only the modest increase of impulse associated with PETN alone.

At about this point in the program, Weibull[26] presented the results of his experiments in which TNT charges were detonated in various vented chambers. The pressure histories very much resembled the Crawshaw-Jones transients for detonations (fig. 13) and his pressures were extrapolated to zero time to obtain the equivalent "mean" pressure, $p_m(o)$, of the blast load; $p_m(o)$ of the reference is unaffected by chamber size and vent area and is therefore analogous to our p_V for constant volume explosions.

In figure 2, $p_m(o)$ is plotted against the explosive loading of the chambers expressed as a charge-volume ratio. The data for the four chambers are approximated by a line,

$$p_m(o) = 166 \left(\frac{Q}{V}\right)^{0.72} \text{ atm}, \tag{19}$$

where Q is the weight of TNT in pounds and V is the chamber volume in cubic feet. For consistency with our own experience with Primacord and to eliminate the fractional exponent from equation 19 we have added the other two lines to figure 2. The dashed line representing

$$p_m(o) = 800 \frac{Q}{V} \text{ atm} \tag{9}$$

[26] Work cited in footnote 14.

conforms to the data for low charge-volume ratios in which the excess fuel from the TNT detonation can burn in the tunnel air. The dotted line representing

$$p_m(o) = 240 \frac{Q}{V} \text{ atm} \qquad (10)$$

is consistent with data for charge-volume ratios large enough to make afterburning in the chamber atmosphere negligible.

Our own values of plateau pressure in Primacord tests (table 17, last column) are also plotted in figure 2. Tests in the air-filled tunnel are shown as solid circles, well-represented by equation 9; the two results with the nitrogen-filled tunnel are shown as solid squares for comparison with equation 10. The pertinence of figure 2 to the assignment of TNT equivalents to gas mixtures has been discussed in the section entitled "Background."

Underground Testing

According to a conventional analysis of structural failure, a tunnel's overburden should be broken if the upward earth movement has attained some critical velocity at the end of the pressure pulse. The South Carolina tests results were too scanty to verify this. Accordingly the South Carolina instrumentation was duplicated in a series of augered tunnels which were subsequently tested near Paris, Pa.; by combining the first four results of this series with the South Carolina results, we obtain table 18, which affords the beginnings of an interpretation.

TABLE 18. - Condensation of soil breakage data

Explosive (1)	Test (2)	Overburden, h (ft) (3)	Impulse, I (psi sec) (4)	I/h (5)	Destruction (6)	Maximum velocity of earth movement (ft/sec)		
						Calculated (7)	Film (8)	Accelerometer (9)
Gas..........	S.C. 1	8	[1]3.6	0.45	No......	-	-	-
	S.C. 3	8	[1]3.9	.49	No......	13	-	-
	Pa. 1	6	3.3	.55	No......	14	5	2
	S.C. 5	8	[1]4.6	.58	No......	12	-	-
	S.C. 7	10	[1]5.7	.57	No......	14	-	[1]3
	S.C. 6	8	[1]5.4	.68	No......	17	10	[1]5
	S.C. 1	5	[1]3.6	.72	Yes.....	-	-	-
	S.C. 4	7	[1]5.4	.77	Marginal	20	16	[1]12,15
Slurry (1.0)[2]	Pa. 3	7½	5.8	.77	Marginal	21	10	26,46
Gas..........	S.C. 2	5	[1]3.9	.78	Yes.....	18	-	[1]23,14
	S.C. 3	5	[1]3.9	.78	Yes.....	23	-	[1]23, 9
	S.C. 5	8	[1]6.5	.81	Yes.....	20	-	-
Slurry (1.5)[2]	Pa. 4	10	9.1	.91	Yes.....	26	26	58
Slurry (2.0)[2]	Pa. 2	7	-	-	Yes.....	>26	42	36,45

[1] From records supplied by the Waterways Experiment Station.
[2] Loading density of slurry, lb/ft of tunnel.

The explosives used were acetylene-air and MAPP-air in tests S.C. 1 through 4 and Pa. 1, MAPP-air-oxygen in tests S.C. 5 through 7, and an AN-water slurry explosive in tests Pa. 2 through 4. The loading density of the slurry in pounds per foot of tunnel length is given in parentheses in the first column of table 18.

A total of 15 observations are listed from the 11 tests because the first three tunnels in South Carolina had two overburden depths--5 ft and 8 ft--at which damage could be assessed at one level of impulse while test S.C. 5 provided 2 levels of impulse at the same thickness of overburden. Columns 3 and 4 of the table list the pertinent overburdens and impulses.

Column 5 lists values of the quotient--impulse I, in psi sec, divided by overburden depth, h, in feet. Column 6 lists "no" destruction at all values of I/h less than 0.7 and either destruction or "marginal" destruction when I/h is more than 0.7.[27] To a first approximation I/h is a relative measure of the maximum upward velocity of the overburden. For if the overburden is assumed to be a frictionless piston of the same width as the tunnel and having a density of 144 lb/ft^3, then

$$I \text{ (psi sec)} = \Delta \text{ (mv)} = mv_{max} = \frac{h\ (144)}{32\,(144)} v_{max} \qquad (20)$$

and $v_{max} = 32$ I/h. (See the section on effect of soil mechanics on earth movement under "Discussion.") A marginal calculated velocity for tunnel destruction appears to be about 20 ft/sec, as shown by column 7 of table 18.

Experimental measurements of earth velocity are given in the two final columns of the table. Column 8 was obtained from motion picture film, the cameras having viewed stakes driven into the overburdens in front of stadia boards (fig. 25 shows the movement of two stakes in the fourth Paris, Pa., test). The numbers of column 9 were obtained by integration of accelerometer records. In general, calculated velocities of column 7 agree about as well with the measured values of columns 8 and 9 as these two columns agree with each other.

DISCUSSION

The Gas Detonation Model

In spite of some failures in detail, the classical one-dimensional model was entirely satisfactory for estimating impulses. Under Experimental Results we pointed out three areas in which data were not in accord with prediction: the values of peak (C-J) pressure; the thickness of the pressure pulse; the duration of the pressure plateau. Let us now consider the significance of these deviations.

[27] No destruction means that the overburden was still intact at ground level although cracks may have appeared along the side; the ground may have lifted transiently as much as a foot but without permanent displacement; the rating--"marginal" destruction--connotes that explosion gases broke through to the surface, leaving a cracked, tilted, noncompetent overburden; in the two such cases listed, the transient upward displacements of the surface were 17 in and 28 in. The rating--"yes"--usually connotes complete destruction in which the tunnel is converted to a trench which is either cleared of overburden or filled with loose clods.

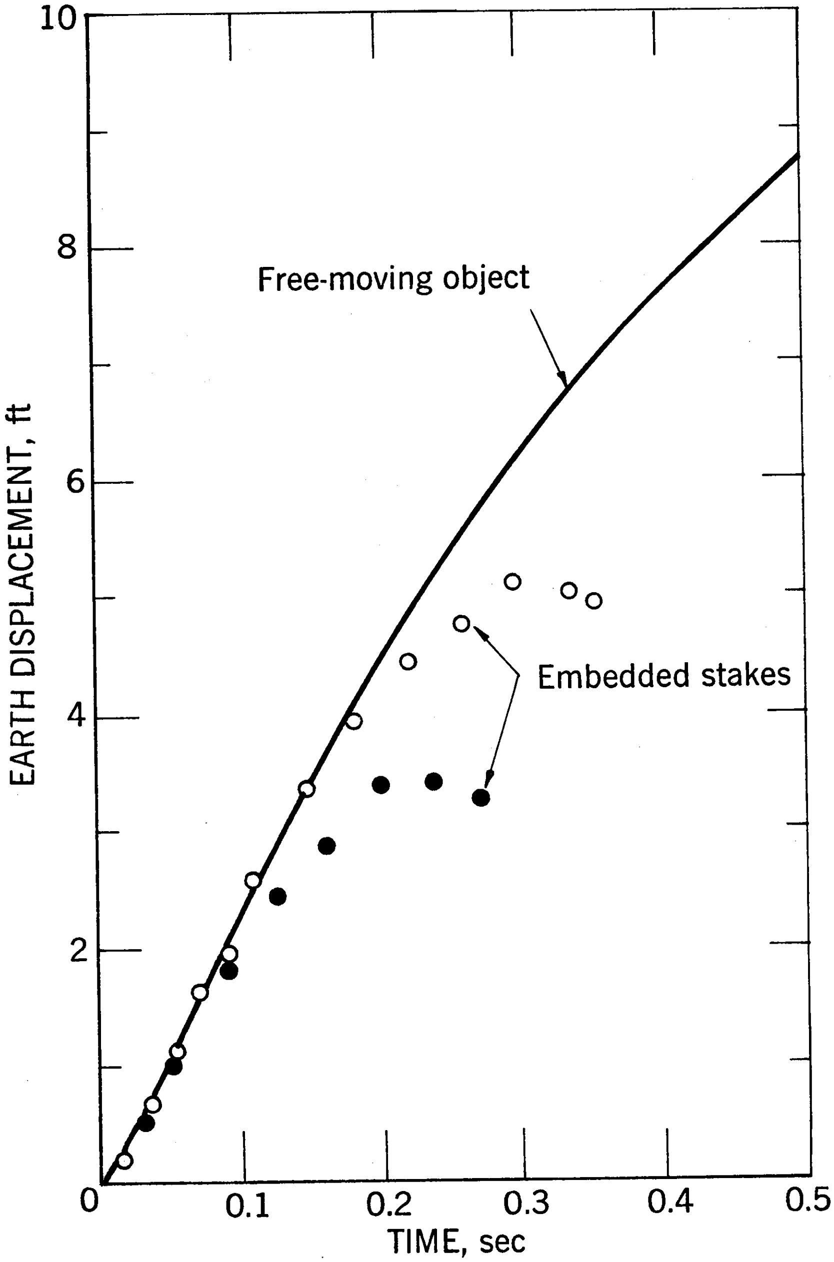

FIGURE 25. - Earth Displacement in Test 4 (Paris, Pa.) Compared With Trajectory of Frictionless Object.

As our pressure instrumentation was designed for long-term (100 to 200 msec) stability rather than for fast response, we expected peak pressures in all cases to be about 3 to 15 psi low at the midpoint of the steel tunnel. In fact, measured pressures were somewhat less on the average than predicted (figs. 21 and 22) but individual values (table 10, station 3) ranged up to 328 psig, far above the computed value. This can be understood only if detonation has departed from an ideal one-dimensional model. A pressure in excess of C-J pressure requires a lateral component directed against the pressure transducer whereas pressures as low as 190 psig occur when the lateral component is directed away from the transducer. Since the pressure peak is of short duration, this phenomenon is of no practical importance.

The decay of pressure from the C-J value to the value in the static gas zone was always 10 to 20 pct slower than predicted by equations which were derived from Taylor.[28] This is possibly due to frictional effects in the long steel tunnel; however, as gas pressures were measured at the wall of the tunnel rather than in midstream, the above observation may relate merely to a boundary layer phenomenon.

[28]Work cited in footnote 10.

The only deviation of practical importance is the short duration of the pressure plateau. In the background section, it was assumed that a static gas zone would expand to fill the 150-ft-long tunnel at the same rate as though the tunnel were prolonged indefinitely and that thereafter, a rarefaction would return at sonic velocity to the pressure station. Evidently, as the pressure pulse emerges from the open end of the tunnel and expands three dimensionally, the movement of burned gas behind the pulse is affected in some way which makes the measured impulses 10 to 20 pct lower than predicted.

Effect of Soil Mechanics on Earth Movement

During Acceleration

A summation of forces on the ceiling of an earthen tunnel is given by Day and Hadala[29] as

$$F = ma + W + V, \qquad (21)$$

where the upward force, F, is given by gas pressure times ceiling area, and is predictable as a function of time. The weight of overburden, W, is given by the overburden thickness and its density. The unbalanced upward force which accelerates the overburden is F-W and its time integral

$$\int_0^{t_1} (F-W)\, dt = \int_0^{t_1} F\, dt - W \int_0^{t_1} dt = I - Wt_1 . \qquad (22)$$

Since W is less than 1 psi per foot of overburden depth, and t_1 is about 0.1 sec, Wt_1 is a small but not negligible correction, 0 to 1.0 psi sec, to such actual impulses as 3.3 to 9.1 psi sec (table 18).

Now, if one can estimate the shear force, V, the acceleration of earth movement, "a," is easily calculated. But unfortunately V is a function of displacement while the lifting force F-W is known as a function of time. To convert V to a function of time requires a mathematical model, a first approximation of which is suggested by Day and Hadala.

For our present purpose, we pretend that V is a simple function of the overburden mass so that equation 21 becomes

$$F - W = ma + V = ma + ma_s = \frac{W}{g}(a + a_s), \qquad (23)$$

where a_s is the deceleration due to the soil's resistance to deformation. Then over the duration of the pressure pulse, t_1,

$$I - Wt_1 = \frac{W}{g}(v'_{max} - v_s) = \frac{W}{g}(v_{max})\ \mathrm{exp}, \qquad (24)$$

[29] Day, J. D., and P. F. Hadala. Destruction of Earthen Tunnels. U.S. Army Engineers, Waterways Experiment Station, Vicksburg, Miss., Miscellaneous Paper No. 1-930, October 1967, 21 pp.

where v'_{max} is calculated from the impulse by assuming v_s is negligible as in column 7 of table 18, and the actual earth velocity, v_{max}, is obtained from photographic and accelerometric records as in columns 8 and 9.

In five tests, calculated v'_{max} averaged 20 ft/sec while v_{max} from photographic records averaged 13 ft/sec. In seven tests, v'_{max} averaged 18 ft/sec while v_{max} from accelerometers averaged 14 ft/sec.

An indication of how well v_{max} was measured photographically is given by figure 25 showing the upward movements of two stakes which had been driven into the overburden directly above tunnel Pa. 4. We think the actual maximum velocity is known within 2 to 3 ft/sec.

During Deceleration

The decelerating movement of the overburden is compared in figure 25 with the trajectory of a free-moving object, such as a loose stone to which the same initial velocity was imparted and which was decelerated only by gravity. The divergence of the points from the curve shows the loss of kinetic energy to shear.

Using the same assumptions as above, the deceleration of the overburden is

$$a(\text{ft/sec}^2) = 32.2 + a'_s, \tag{25}$$

in which a'_s may be the same as a_s in equation 23. The total duration of this phase of earth movement must be

$$t_2 = v_{max}/a \tag{26}$$

and the peak displacement

$$S = \frac{1}{2} a \ (t_2)^2. \tag{27}$$

Figure 26 compares the photographically determined displacements in five tests with a line calculated on the assumption that $a'_s = 0$. The two lower points represent tests in which the ground surface was unbroken although cracks did appear to the side. These points are in good agreement with the calculated line.[30]

The three upper points on the graph represent cases where the ground surface was broken. Test S.C. 4 seems particularly appropriate to consider because the observed result was a single cleavage plane above the axis of the tunnel; the measured v_{max} was 16 ft/sec and the total ground movement was 2.4 ft. By equations 26 and 27, a = 53 ft/sec^2. Thus "a" is less than twice the gravitational constant and the deceleration produced by one plane of shear is

[30] In a third test, S.C. 6, the initial velocity was 10 ft/sec from which the calculated rise was 17 in; the stake movement was followed to 13 in, at which point it was obscured by a cloud of dust.

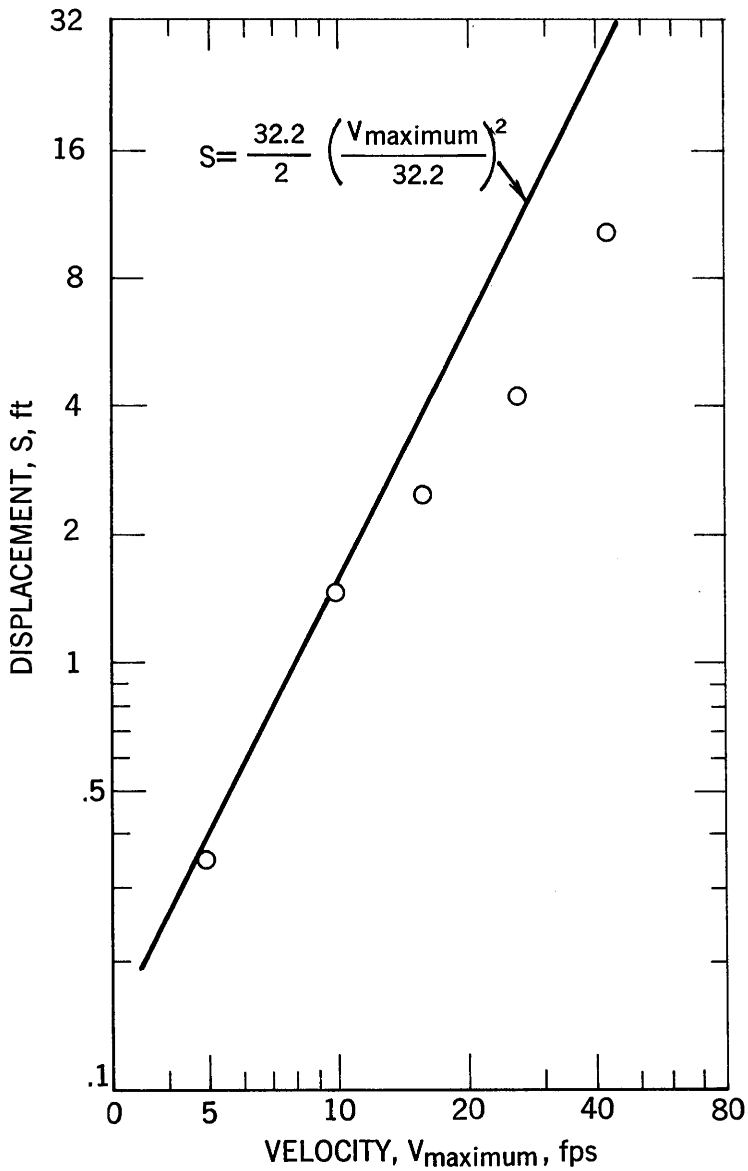

FIGURE 26. - Maximum Overburden Displacement as a Function of Soil Velocity for Earthen Tunnels.

less important than the weight of the soil. At v_{max} = 26 ft/sec (test Pa. 4) and v_{max} = 42 ft/sec (test Pa. 2), "a" was 81 and 88 ft/sec^2, respectively, as the overburden was converted to rubble.

Until an analytical model has been developed to solve equation 21 for earth acceleration, we recommend the following:

1. If one's concern is with the accidental destruction of an earthen structure (sewer, tunnel, etc.) by an explosion, omit any consideration of soil mechanics. This gives a small overestimate in calculating the overburden movement.

2. If one's concern is the intentional demolition of an overburden, assign a_s and a'_s the same value as the gravitational constant, 32 ft/sec^2. This gives a small underestimate of earth movement.

3. If the earthen structure is comparable to the clay overburdens of our experiments, destruction will occur if v_{max} is more than about 20 ft/sec.[31]

4. Again judging from our 5- to 10-ft depths of overburden, an upward displacement of 20 pct of the soil thickness may occur without breakage.

[31] A velocity of 20 ft/sec was accompanied by earth breakage in other tests with 20 ft of overburden but not in tests with 30 ft of overburden.

Pressure and Energy as Destruction Criteria

A striking observation from the tunnel tests was the very small fraction of the explosion energy that was utilized in causing the overburden to fail. Consider that

$$\int_{V_0}^{V_1} pdV \geq \tfrac{1}{2}\, m \left(v_{max}\right)^2, \qquad (28)$$

where V_1 is the tunnel volume at the point in time that a critical v_{max} was attained. From acceleration records of tests 2 and 3 of the South Carolina series, V_1 was $16\tfrac{1}{4}$ ft^3 while the initial volume, V_0, was 15 ft^3 per linear foot of tunnel. The value of the work integral between these limits is shown in figure 27 as the cross-hatched area under curve p_0p_1, that is, 106 psi ft^3 or 4.95 kcal per foot of tunnel. For comparison, the kinetic energy of the overburden, $\tfrac{1}{2}$ m $(v_{max})^2$ was 4.45 kcal and the accompanying increase of potential energy 0.13 kcal per foot of tunnel.

But in a tunnel of 15 ft^2 cross section, 4.95 kcal per foot is equivalent to 9 cal/g of explosive mixture; that is, about 1 pct of the $-\Delta H_{298}$ of 842 cal/g. It seems unlikely that the process of destruction could ever be energy limited.

Suppose now that the tunnel had a cross section 3 ft wide by $2\tfrac{1}{2}$ ft high so that V_0 is halved and the total chemical energy of the explosion is halved. Figure 27 shows the gas expansion as curve $p_0''p_1''$. Although the pressure does fall by twice as much during the expansion, this change is insignificant compared with initial pressure, and the work output is only 4 pct less. Stated differently, the overburden is almost as likely to fail with the $7\tfrac{1}{2}$-ft^2 cross section of tunnel as with the 15-ft^2 cross section because the failure mechanism is pressure limited, and pressure (by equations 9 and 10, fig. 2) is directly proportional to <u>energy density,</u> C/V, not to total energy.

Likewise, if we compare the work integral for the oxygen-augmented mixture of test S.C. 6 which is the area under p_0'/p_1' with the area under p_0p_1 the relative energies utilized in the two explosions are given almost exactly by the pressure ratio, p_0'/p_0. Furthermore, if one changed from stoichiometric acetylene-air containing 7.75 pct acetylene to stoichiometric acetylene-oxygen which contains 28.5 pct acetylene, the pressure change, 1.8-fold, would not be in the ratio of chemical energies, 28.5 to 7.75. This is because the acetylene-oxygen product temperature is above the range covered by figure 2; the energy absorbed by endothermic dissociations is only recovered as the explosion products cool; the recovered energy should contribute to air blast and to fragment velocities but not to failure of the earthen structure.

TNT Equivalence of Explosive Gas Mixtures

Damage to the Confining Structure

The remarks in the sections on the effect of soil mechanics on earth movement and pressure and energy as destruction criteria should pertain to the

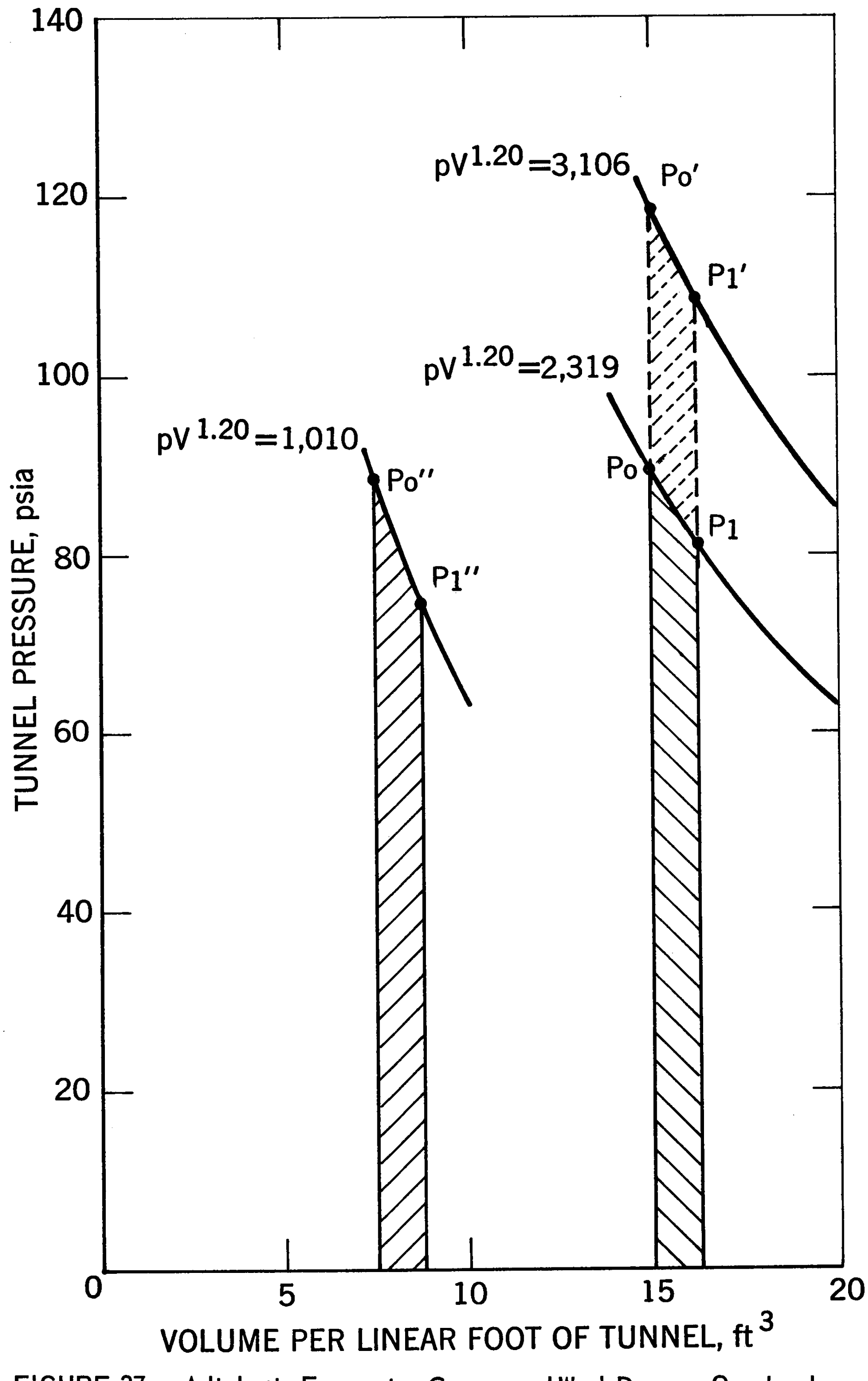

FIGURE 27. - Adiabatic Expansion Curves and Work Done on Overburdens During 1.25-Ft^2 Enlargement of Tunnel Cross Section.

failure of any structure in which the walls have sufficient competence to demand the full pressure of the exploding gas. This pertains to underground explosions as in sewers, mines, and fortifications; also in pressure vessels which are nearly strong enough to withstand the explosion as in the case of the Ponca City dephlegmator.[32]

The effective pressure represented by p_m (o) is proportional to energy density, $\Delta H/V_o$. Therefore in a given (unvented) volume of structure, destruction is usually determined by ΔH; it should make little difference whether the incident is a gas deflagration, a gas detonation, or the detonation of a condensed explosive centrally located. If the vessel is vented, the full explosion pressure may not be developed by deflagration, but gas phase and

[32]Work cited in footnote 5.

condensed phase detonations should be about equally damaging to the structure if the ΔH's are equal.

Damage Outside the Structure from Air Blast and Fragments

The maximum blast and fragment energies are given by areas under the gas expansion curves (fig. 27) extended to ambient pressure; these curves should reflect exothermic reactions during product cooling and be related to the total chemical energy release.

One finds great differences between gas deflagration and gas detonation when the confining walls give way at low pressure. The work which can go into air blast and fragments, designated "pressure energy,"[33] is given approximately by

$$W = \frac{p_e V_e - p_a V_a}{\gamma - 1} \quad (29)$$

for adiabatic expansion of the products to ambient pressure, p_a. In detonation, the effective pressure p_e is relatively unaffected by early failure of the walls whereas in deflagration p_e can be low and much of the chemical energy dissipated by ordinary convection.

In the limiting case of an unconfined fuel gas-air mixture, such as in a cryogenic spill or the rupture of a gasline, it is difficult to visualize detonation except through the agency of a very strong initiating source such as lightning or the explosive boosters listed in table 8. The hazard of deflagration is likely to be from other factors than from pressure transients since in equation 29 the difference between p_e and p_a must be small. Some overpressures have been measured in proximity to unconfined hydrogen-air ignitions[34] and correspond only to modest wind velocities.

To recapitulate, if a gas mixture is strongly confined its TNT equivalent may be figured from its heat of combustion, ΔH, and the appropriate ΔH for TNT. If the mixture is unconfined and initiating sources for detonation can be discounted, the TNT equivalent is nearly zero. In the intermediate case of weak confinement, the TNT equivalent of a detonating gas mixture is given by the heat of combustion while that of a deflagration is given by the much lower value of "pressure energy."

CONCLUSIONS

On review of our experiments in several test chambers, we consider the major findings and conclusions to be:

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[33] High, W. G. The Design and Scale Model Testing of a Cubicle to House Oxidation or High Pressure Equipment. Chem. and Ind., June 3, 1967, p. 899.

[34] Zabetakis, M. G., and D. S. Burgess. Research on the Hazards Associated with the Production and Handling of Liquid Hydrogen. BuMines Rept. of Inv. 5707, 1961, 50 pp.

1. Three representative hydrocarbon mixtures--acetylene-air, MAPP-air, and propane-air--were all initiated to detonation by 10-g boosters at all concentrations within their limits of flammability.

2. All hydrocarbon fuels studied--acetylene, MAPP, propane, and gasoline--gave nearly the same average impulse over a range of fuel concentrations in their mixtures with air.

3. The largest impulses were found generally with slightly fuel-lean mixtures.

4. Pressures and impulses can be predicted with adequate accuracy for any practical purpose from a textbook model of gas detonation:

   a. Assuming the C-J pressure to be twice the pressure of constant volume combustion.

   b. Assuming a Taylor expansion behind the C-J plane in which (1) the use of a "frozen" gamma leads to about 10- to 20-pct underestimate of the pressure plateau in the static gas zone, while (2) the duration of the pressure plateau (downstream end of duct open) is about equally overestimated.

5. The movement of earthen confining structures is calculable within a factor of 2 to 3 in velocity without any reference to soil mechanical factors. In a variety of clay overburdens the resistance imposed by shear is about equal to overburden weight.

6. The TNT equivalence of a confined gas mixture is slightly overestimated by comparing its heat of combustion with the appropriate ΔH for TNT.