CONF 8106..-23

LA-UR -81-1725

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AUTHOR(S): J. N. Johnson

SUBMITTED TO: 1981 Topical Conference on Shock Waves in Condensed Matter, Menlo Park, CA, June 23-25, 1981

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

CALCULATED SHOCK PRESSURES IN THE AQUARIUM TEST*

J. N. Johnson
Los Alamos National Laboratory, Los Alamos, NM 87545

ABSTRACT

A new method of analysis has been developed for determination of shock pressures in aquarium tests on commercial explosives. This test consists of photographing the expanding cylindrical tube wall (which contains the detonation products) and the shock wave in water surrounding the explosive charge. By making a least-squares fit to the shock-front data, it is possible to determine the peak shock-front pressure as a function of distance from the cylinder wall. This has been done for 10-cm and 20-cm-diam ANFO (ammonium nitrate/fuel oil) and aluminized ANFO (7.5 wt% Al) aquarium test data.

INTRODUCTION

The aquarium test of explosive performance consists of optical measurement of detonation velocity, shock-wave position, and expansion rate of the pipe containing the test product. These experiments have been described in a report by Craig, et al.[1] The expansion of the tube wall gives information on the equation of state of the detonation products, and this has been used to good advantage in determining the performance properties of ANFO.[1] The shock wave in water contains information on peak shock pressure delivered to the surrounding medium, and much less has been done with this information. The angle between the shock front and the cylinder axis is maximum at the pipe wall and monotonically decreases with increasing distance from the pipe wall. This is a consequence of higher shock pressures near the cavity wall and the dependence of shock velocity on compression. This information is used here to calculate pressure as a function of radius at the expanding shock front in a number of ANFO and aluminized ANFO aquarium tests.

Explosive initiation is assumed to take place at the top of a cylindrical column. In a downward-moving coordinate system traveling with steady detonation velocity D, the detonation wave appears to be stationary, with material below flowing upward at velocity D, as shown in Fig. 1. The shock velocity at point A is given by U. The unit normal and unit tangent vectors at point A are $\hat{n}$ and $\hat{t}$, respectively. If the shock wave in the water is steady (that is, unchanging in shape), it is also stationary in this coordinate system and the relationship between U and D becomes

$$U = D \cdot \sin \theta. \qquad (1)$$

In this stationary coordinate system, material ahead of the shock is moving at velocity $-D \sin \theta$ and $D \cos \theta$ relative to the $\hat{n}$ and $\hat{t}$ axes.

*Work supported by the U.S. Department of Energy.

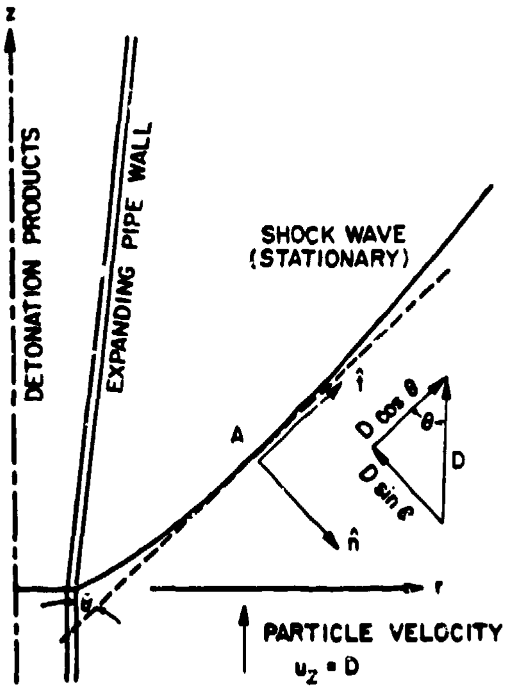

Fig. 1. Stationary shock front and expanding pipe wall in coordinate system moving downward at velocity D.

The Rankine-Hugoniot jump conditions for the cylindrically diverging, curved shock front shown in Fig. 1 can then be written as[2]

$$\rho u = -\rho_0 D \sin \theta \quad , \tag{2}$$

$$v = D \cos \theta \quad , \tag{3}$$

$$p + \rho u^2 = \rho_0 D^2 \sin^2 \theta \quad , \tag{4}$$

$$(u^2 + v^2)/2 + e + p/\rho = D^2/2 \quad , \tag{5}$$

where u and v are velocity components in the $(\hat{n},\hat{t})$ coordinate system, ρ is the material density, p is the pressure, and e is the internal energy per unit mass, all evaluated behind the shock, and ρ_0 is the undisturbed density of the material ahead of the shock (at zero pressure and zero internal energy). From Eqs. (2)-(5), the internal energy change across the oblique shock of Fig. 1 is given by

$$e = (p/2)(1/\rho_0 - 1/\rho) \quad , \tag{6}$$

which is exactly the same as that for a normal shock. Therefore, the pressure-volume states for the oblique shock lie on the Hugoniot curve determined by one-dimensional plane shock-wave experiments;

$$p = \frac{\rho_0 c_w^2 \varepsilon}{(1 - s\varepsilon)^2} \quad , \tag{7}$$

where $\varepsilon \equiv 1 - \rho_0/\rho$, $\rho_0 = 1.0$ g/cm^3, $c_w = 0.148$ cm/μs is the acoustic (low amplitude sound) wave velocity in water, and $s = 2.0$ is the slope of a straight-line fit to the shock velocity-particle velocity data for water.[3] From Eqs. (2) and (4), it is found that

$$p = \rho_0 D^2 \sin^2 \theta\varepsilon \quad , \tag{8}$$

and hence, from Eqs. (7) and (8),

$$p = \rho_0 D^2 \sin^2 \theta (1/s)[1 - c_w/(D \sin \theta)] \quad , \tag{9}$$

which gives the pressure behind the shock wave when the steady detonation speed D and the angle θ between the shock and the cylinder axis are known.

The angle θ is obtained from a fit of the shock front data to an expression of the form

$$r = r_0 + \tan\theta_{min}\left[z + \frac{1}{a}\left(\frac{\tan\theta_{max}}{\tan\theta_{min}} - 1\right)\left(1 - e^{-az}\right)\right] \quad , \qquad (10)$$

where

$$\tan\theta_{min} = \frac{C_w/D}{\sqrt{1 - (c_w/D)^2}} \quad , \qquad (11)$$

and a and $\tan\theta_{max}$ are the two parameters determined by the method of least squares.[4] The angles θ_{max} and θ_{min} have the physical interpretation of being the values of θ at ($z = 0$, $r = r_0$) and as r (and z) $\to \infty$, respectively.

The expanding-pipe-wall data is fit to a linear expression of the form

$$r = r_0' + (\bar{V}/D)z \quad , \qquad (12)$$

where D is again the detonation speed, and r_0' and $\bar{V}$ are constants determined by the method of least squares. For a steady propagating detonation (without change in shape of pipe wall or shock-front positions) in the negative z-direction,

$$r(z,t) = r_0' + (\bar{V}/D)(z + Dt) \quad , \qquad (13)$$

and the outward pipe velocity is given by

$$dr/dt = \bar{V} \quad . \qquad (14)$$

Shock front and pipe-expansion data for an aquarium test on ANFO (Gulf N-C-N 100, Gulf Oil Chemicals Co., Miriam, Kansas) contained in a 10-cm-i.d. clay pipe are shown in Fig. 2a along with the least-square fits; the ordinate in this figure is Z/D, the time behind the assumed steady propagating detonation front. The calculated shock pressure as a function of radial position is shown in Fig. 2b. A summary of initial density, detonation velocity, $\bar{V}$, and P_{wall}, the calculated shock pressure at the pipe wall, is given in Table I.

DISCUSSION

The calculated shock pressures at the pipe wall depend on initial density and charge diameter, as expected. The effect of aluminization on explosive performance is difficult to access from the data presented here, but remains an important one to try to quantify.

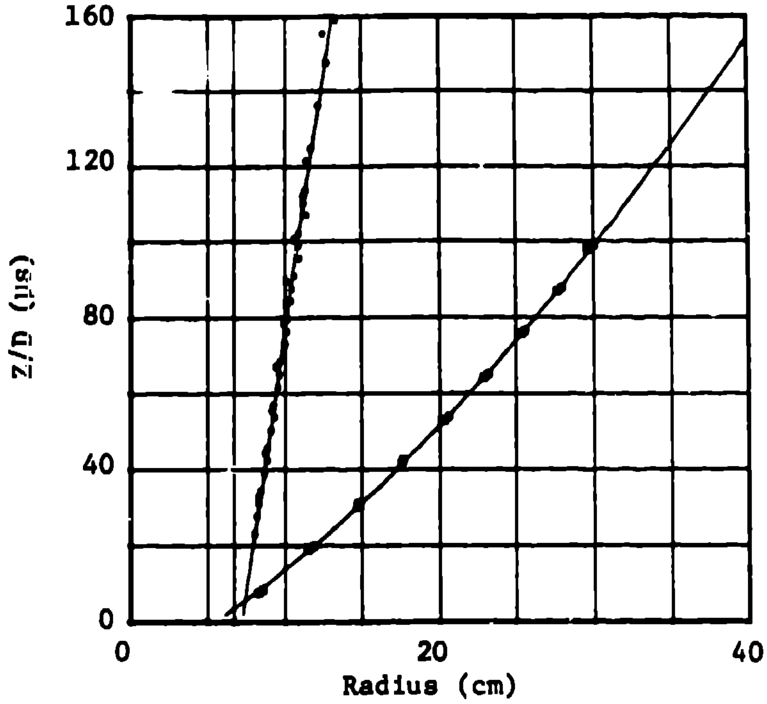

Fig. 2a. Shock front and pipe expansion data for aquarium test 4652 (ρ_0 = 0.90 g/cm^3) with least-square fits (solid lines).

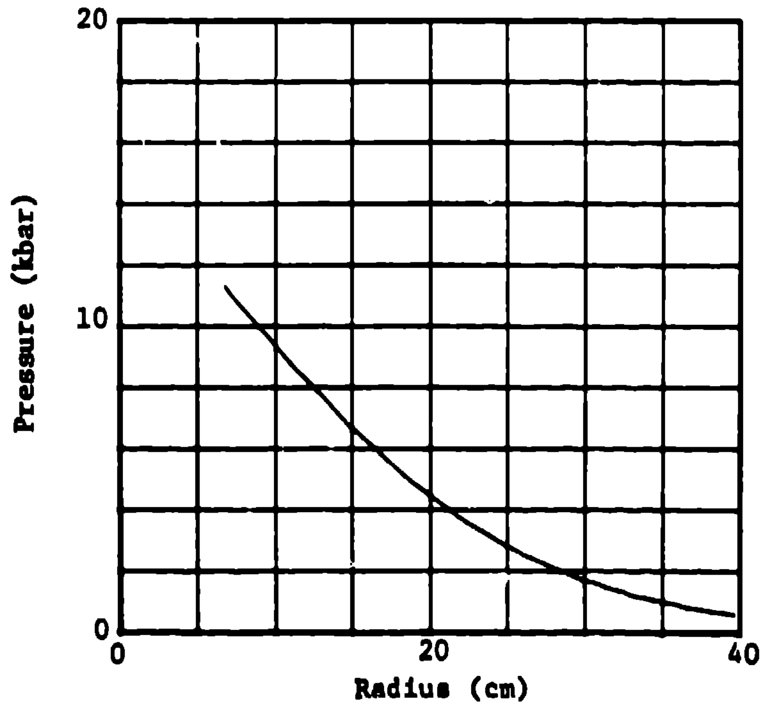

Fig. 2b. Calculated shock pressure as function of radial position.

Table I. Summary of ANFO aquarium tests: clay pipe confinement

Experiment	Diameter (cm)	ρ_0 (g/cm^3)	D (km/s)	$\bar{V}$ (km/s)	P_{wall} (kbar)
4678	10	0.79	3.27	0.34	8.9
4724*	10	0.87	3.63	0.42	9.3
4652	10	0.90	3.47	0.37	11.3
4768	10	0.93	3.60	0.39	11.7
4688	20	0.79	3.78	0.39	12.3
4707*	20	0.88	3.98	0.50	16.0
4664	20	0.90	4.12	0.43	15.0
4700	20	0.90	4.15	0.47	15.8
4752*	20	1.11	4.24	0.51	19.5

*7.5 wt% aluminum (Gulf N-C-N 750).

Experimental work is continuing on the actual time-resolved measurement of shock pressures for well characterized aluminized ANFO explosives. Combination of these measurements with the analysis presented here will provide a check on data consistency as well as unambiguous information on the role of aluminum in improving explosive performance.

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