

## EXPLOSIVE BEHAVIOR OF AMMONIUM PERCHLORATE

Donna Price, A. R. Clairmont, Jr., and I. Jaffe

U. S. NAVAL ORDNANCE LABORATORY  
White Oak, Silver Spring, Maryland

The inorganic oxidizer, ammonium perchlorate (AP), is widely used as a major propellant ingredient. It is, in addition, a very interesting high explosive because its behavior differs markedly from that of conventional explosives such as TNT. AP is a member of a group of explosives which exhibit more ideal detonation behavior at high than at low porosity.<sup>1</sup> No member of this group has been studied very systematically; only a careful investigation of typical members will enable us to understand these materials at least as well as we understand more conventional explosives. Because AP seems a representative group member, because it is frequently used as a propellant component, and because it has been extensively studied in the related fields of thermal decomposition and combustion, we have started a systematic study of its explosive behavior. The purpose of this paper is to report the results obtained from our recent work.

The detonation of AP has been studied before, chiefly by Andersen and Pesante.<sup>2</sup> But their data had too much scatter, and did not extend sufficiently far into the high charge density region to demonstrate the distinctive explosive behavior defined by the present results. That behavior is typified by a detonability limit curve along which critical density increases with critical diameter, and a finite diameter detonation velocity which is not uniquely defined by loading density, i.e., which exhibits a non-linear curve with a maximum in the detonation velocity.

## EXPERIMENTAL

All ammonium perchlorate used was propellant grade; it contained 0.2 to 1% tricalcium phosphate. The three lots of perchlorate had weight-median particle sizes of 10, 25, and 200  $\mu$ , respectively. For charge preparation, the material was dried at 50°C for four hours or longer and packed in cellulose acetate envelopes to form 20.32 cm-long cylinders of 1.90 to 7.62 cm diameter. Compacting was by hand, by hydraulic press, or by isostatic press (followed by machining to size), according to the charge density desired and the grain size of the perchlorate. All low density charges were fired almost immediately after preparation to avoid the formation of small cracks and column separation, phenomena which occur with aging.

The best quality charges were, of course, those prepared in the isostatic press from the 10  $\mu$  material. As the grain size of the perchlorate increased or as the charge density ( $\rho_0$ ) decreased, charge quality became poorer. At  $\rho_0 < 1$  g/cc, the charges were of such poor quality that only a few small diameter charges prepared from the 10  $\mu$  material were accepted for firing.

The charges were fired in the experimental setup of Fig. 1 with either tetryl or pentolite boosters. A 70 mm smear camera was used to record the flasher enhanced luminosity of the reaction front. The camera was used at a writing speed of between 1 and 3 mm/ $\mu$ sec to obtain a

smear trace of the disturbance at  $45^\circ$  to the base of the film.

The smear camera photographs were of excellent quality, and detonation velocity was determined from the slope of the trace, i.e., by a least square fit of the linear distance - time data. For the lowest resolution, the maximum error estimated from error in reading these records is 1.5%. In over a dozen replications the maximum deviation was also 1.5%; the mean precision was 0.7%.

## RESULTS AND DISCUSSION

### Failing Reactions

The first interesting result of this work is that charges of ammonium perchlorate (of any grain size) when subcritical are nevertheless capable of showing fading but vigorous reaction. Such charges of the  $10\ \mu$  and  $25\ \mu$  materials, under shock from the booster, produced curved luminous traces persisting to distances as large as 8 - 9 diameters down the charge. As the charge diameter was increased toward its critical value, the curvature of the trace decreased. It was, therefore, almost impossible to determine the exact critical limits for the perchlorate; instead, they were bracketted by two densities at which failure and detonation occurred at a given diameter.

The coarsest material ( $200\ \mu$ ) failed to detonate at its pour-density of  $1.29\ \text{g/cc}$  in a  $7.62\ \text{cm}$  diameter charge. (Larger charges cannot be used in the available firing facilities.) However, it too showed vigorous reaction persisting for two diameters down the charge.

### Detonability Limits

The limit or failure curve for the  $10\ \mu$  perchlorate in the charge diameter ( $d$ ) vs  $\rho_0$  plane is approximated in Fig. 2. The critical values are  $d_c$ , the diameter at and above which detonation propagates, and  $\rho_c$ , the density above which detonation cannot occur. The trend of increasing critical density with increasing critical diameter and the consequent definition of  $\rho_c$  are both opposite to those for TNT-like explosives.<sup>1</sup> Figure 2 also shows measurements made by two other investigators on fine AP's. The agreement is very good in view of approximating the particle size distribution by the median size and of the difficulty of determining that median.

The limit curve for the  $25\ \mu$  AP was not as well defined as that for the finer material. The relevant data are:

<u>d(cm)</u>	<u><math>\rho_0</math>(g/cc)</u>	
	<u>Deton.</u>	<u>Failure</u>
3.81	1.02	1.11
5.08	1.36	1.41
7.62	1.47	1.56

This limit curve will therefore lie above and to the left of that for the finer perchlorate. The limit curve for the  $200\ \mu$  material is beyond the experimental range of the present work. The trend of particle size effect is the expected one for all explosives, that of increasing  $d$ .

with increasing particle size. The shift in  $\rho_0$  is, however, toward lower values for ammonium perchlorate, toward higher for TNT-like explosives.

### Detonation Behavior Pattern

The detonation velocity ( $D$ ) vs  $\rho_0$  curves at various diameters of the finest perchlorate are shown in Fig. 3. Typically the  $D$  vs  $\rho_0$  curve at fixed  $d$  shows detonation velocity increasing with increasing density to a maximum value. Beyond this maximum,  $D$  decreases as  $\rho_0$  increases until it reaches its critical value at the failure limit.

The curve for each diameter has been terminated at the critical density given by the smoothed curve of Fig. 2. The limit line of Fig. 3, which divides the detonation from the failure area, is shown as the dashed line through these terminal points. The curve seems slightly concave upward and gives the critical detonation velocity ( $D_c$ ) as a function of  $\rho_0$  at different diameters, but at fixed particle size.

Fig. 4 shows the analogous pattern, analogously derived, for the 25  $\mu$  material. This pattern is very like that of Fig. 3; it is, however, compressed into the smaller diameter range which results from the particle size shift of the limit curve,  $d$  vs  $\rho_0$ . At any given values of  $d$  and  $\rho_0$ , the detonation velocity of the finer perchlorate is greater than that of the coarser. This point is further illustrated in Fig. 5 where the particle size effect on the  $D$  vs  $\rho_0$  curves at  $d = 5.08$  cm is shown. The terminal points of the two curves are on a limit curve (indicated by the dashed line) which gives  $D_c$  vs  $\rho_0$  at constant diameter but at different particle sizes.

### Infinite Diameter Values

Since most of our  $D$  vs  $\rho_0$  curves are non-linear, our experimental range is one in which diameter effect on  $D$  is large. At  $\rho_0 = 1.0$  g/cc all data are on the low density side of the maximum  $D$  or, in one case, at the maximum. Under these circumstances, the usual  $D$  vs  $d^{-1}$  curve is linear (Fig. 6) and gives the ideal value  $D_1$  of 3.78 mm/ $\mu$ sec at  $\rho_0 = 1.01$  g/cc in good agreement with the comparable value of 3.75 determined by Evans et al.

For an analogous selection of data at  $\rho_0 = 1.26$  g/cc the solid symbols of Fig. 6 are from the high density side of the maximum  $D$  and must be neglected; they would lead to values of  $D_1$  which are too high. The remaining data give  $D_1 = 4.79$  mm/ $\mu$ sec at  $\rho_0 = 1.25$  g/cc in very poor agreement with the Ref. (2) value. However, if the Ref. (2) data are extrapolated as in the present work, the analogous  $D_1$  is 4.85 instead of the reported 4.37 mm/ $\mu$ sec.

Even so, it is quite likely that the  $D_1$  value obtained in this manner at the higher density (where detonation behavior is less ideal) is too high. Measurements at larger diameters are necessary to decide this. Meanwhile the present values have been used in Figs. 3 and 4 to indicate a portion of the  $D_1$  vs  $\rho_0$  curve. The data for the 25  $\mu$  material also extrapolate to the same curve.

### Reaction Zone Lengths, Reaction Times

Of the available diameter effect theories, the curved front theory<sup>7a</sup>

seems to fit our data best. Ref. (7) gives the detonation reaction zone length by

$$a = d (1 - D/D_1) \quad (1)$$

The modified theory<sup>a</sup> gives a zone length

$$z = (s/3.5) (1 - D/D_1) \quad (2)$$

where  $s$  is the radius of curvature of the reaction front. For the reasonable assumption that  $s$  is directly proportional to  $d$ , Eqs. (1) and (2) are identical except for a constant factor and will lead to the same relative reaction zone lengths.

The reaction time ( $\tau$ ) is defined and related to the reaction zone length by

$$a = (D - \bar{u}) \tau \quad (3)$$

where  $\bar{u}$  is the average particle velocity between the leading von Neumann shock and the C-J plane of the detonation front. Moreover, according to the grain burning theory<sup>7</sup>,

$$\tau = R/\lambda k \quad (4)$$

where  $R$  is the average particle radius,  $\lambda$  the molecular diameter, and  $k$  the specific reaction rate of a single molecule.

For each ideal value  $D_1(\rho_0)$ , there is a corresponding detonation temperature  $T_1(\rho_0)$ . Moreover, these infinite diameter values are independent of the grain size. Hence Eqs. (1) or (2) and (3) can be used to obtain the ratio of the reaction times of the 10  $\mu$  and 25  $\mu$  perchlorate at  $T_1$ . If in addition we assume that this material detonates by a grain burning mechanism, we can incorporate Eq. (4) into the relations to obtain

$$(a_1/a_2) = (z_1/z_2) = (\tau_{11}/\tau_{21}) = (R_1/R_2) \quad (5)$$

where the subscripts 1 and 2 denote 10  $\mu$  and 25  $\mu$  ammonium perchlorate, respectively. Calculation of the ratio of the reaction times by Eq. (5) gives  $(\tau_{11}/\tau_{21}) = 0.40 \pm 0.04$  over the range of  $0.90 \leq \rho_0 \leq 1.20$  g/cc. This is in good agreement with the ratio  $(R_1/R_2) = 10/25 = 0.40$ , a result consistent with the grain burning mechanism for the detonation of this material; such a mechanism is also consistent with its more ideal behavior at greater porosities.

## REFERENCES

- (1) D. Price, "Contrasting Patterns in the Behavior of High Explosives," Eleventh Symposium (International) on Combustion (1967) pp 19-28, in press.
- (2) W. H. Andersen and R. E. Pesante, "Reaction Rate and Characteristics of Ammonium Perchlorate in Detonation," Eighth Symposium (International) on Combustion, Williams and Wilkins Co., Baltimore (1962) pp 705-10.
- (3) R. L. Jameson, S. J. Lukasik, and B. J. Pernick, J. Appl. Physics 35, 714-720 (1964).
- (4) M. W. Evans, C. M. Ablow, B. O. Reese, and A. B. Amster, "Shock Sensitivity of Low Density Granular Explosives," Proceedings of the International Conference on Sensitivity and Hazards of Explosives, Ministry of Aviation, U. K. (1963).
- (5) M. W. Evans, B. O. Reese, L. B. Seely, and E. L. Lee, "Shock Initiation of Low-Density Pressings of Ammonium Perchlorate," Proceedings of the Fourth Symposium on Detonation, October 1965, in press.
- (6) M. L. Pandow, K. F. Ockert, and H. M. Shuey, "Studies of the Diameter-Dependence of Detonation Velocity in Solid Composite Propellants I, Proc. of the 4th Symposium on Detonation, October 1965, in press.
- (7) H. Eyring, R. E. Powell, G. H. Duffy, and R. B. Parlin, Chem. Revs. 45, 69 (1949).
- (8) W. W. Wood and J. G. Kirkwood, J. Chem. Phys. 22, 1920 (1954).

FIG. 1 EXPERIMENTAL ASSEMBLY

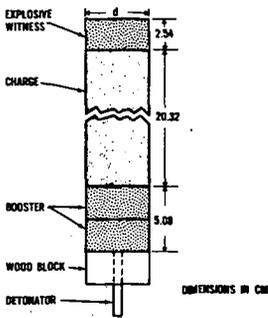


FIG. 2 DETONABILITY LIMIT CURVE FOR AP (10 $\mu$ )

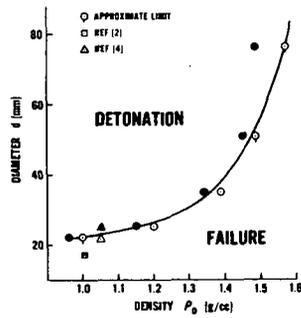


FIG. 3 DETONATION BEHAVIOR OF AP (10 $\mu$ )

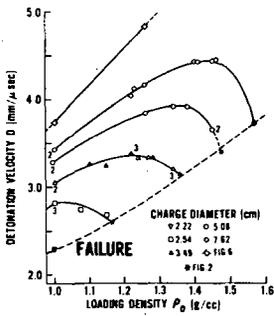


FIG. 4 DETONATION BEHAVIOR OF AP (25 $\mu$ )

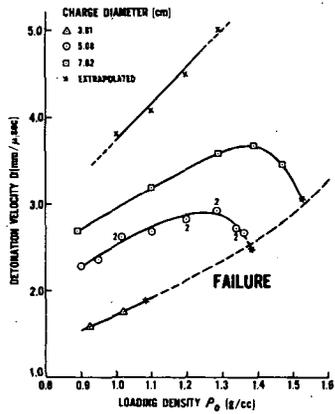


FIG. 5 EFFECT OF PARTICLE SIZE ON DETONATION VELOCITY OF AP (d=5.08 cm)

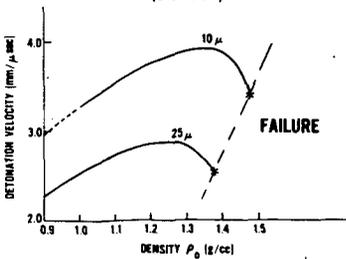


FIG. 6 EXTRAPOLATION TO INFINITE DIAMETER VALUES

