Rather it is believed to be a mechanism of the higher rate type occurring in detonation. The linear burning rate for TNT in normal explosive deflagration is given by

$$\frac{dR_g}{dt}(\text{cm/sec}) = 2.07 + 1.20 \times 10^{-2} p(\text{atmos}), \quad (24)$$

which has been carried out experimentally for pressures roughly as great as the maximum attained in the cannon.

The average radius of the 4–6 pellets was about 0.2 cm. Thus if one assumes a reaction time of 500 μsec, the burning velocity of the TNT in the cannon would be 400 cm/sec. Using Eq. (24) and a value of 5470 atmos, the calculated maximum pressure that may be obtained in the cannon under conditions of uniform filling of the chamber, one calculates a burning rate of only 68 cm/sec, or about $\frac{1}{6}$ the rate measured in the cannon. The measured pressures, except possibly for a short period at the start of the reaction, were at all times somewhat lower than this; probably due to cannon leakage.

The possibility was considered early in this study that the reaction process observed in the cannon method may be simply normal explosive deflagration in a much finer mesh product resulting from fragmentation of the explosive grains by the initial transient detonation. However, experimental results show that the amount of fragmentation produced by the initial detonation if any is not large. Indeed, the assumption that mechanical fragmentation of the coarse TNT particles should not be appreciable during the interval of time covered by the cannon experiment seems entirely justified from the fact that solids fragment primarily only in tension rather than in compression. Moreover, the fact that particle size effects were observed in the first place, and that these effects were directly related to the particle sizes used argue against appreciable fragmentation; it would be fortuitous indeed if fragmentation were to occur such as to give fragmented particles of sizes reproducibly in direct proportion to the original size. As a matter of fact, the coarse-grained TNT used in this test was not easily fragmented owing to its excellent spherical shape and nonporous character. One should also realize that the general applicability of the Eyring surface burning law in detonation shows that particles are not broken up by the shock front in detonation.

A 40 gram sample of 4–6 mesh TNT was fired in the cannon without the slug, i.e., with the barrel open, using a No. 8 electric blasting cap. Considerable unreacted TNT was blown out of the chamber and could not be recovered, but that (8 grams of the original charge) remaining in the cannon showed very little evidence of breakup. Moreover, when one fires a charge containing both fine and coarse TNT in the cannon without the slug, the drop in pressure and temperature following detonation are sufficiently sharp that reaction cuts off in the early stages. Under these conditions little explosive remains in the chamber, but particles blown out of the cannon have been found and examined; while they were invariably blackened by reaction at the surface, they showed surprisingly little evidence of particle fragmentation despite the drastic conditions to which they were exposed.

TABLE IV. Studies of the fragmentation of inert substances in mixtures with TNT or RDX detonated in the cannon.

Particle size	Fine TNT, 15 grams borax beads (14–20 mesh), 40 grams Percent recovered	Fine RDX, 10 grams quartz (20–28 mesh), 40 grams Percent recovered
−4+6	...	...
−14+20	51	...
−20+28	11	28
−28+35	3	13
−35+48	2	17
−48+65	1	13
−65	4	29
Lost	27	1

Low density mixtures consisting of fine TNT or RDX and inert substances of known initial particle size were detonated in the cannon with a No. 8 cap. In these studies the barrel was plugged to prevent blowout of the solid particles (although some of the material was found to blow out the cap wire openings). The solid residue recovered from the cannon was carefully sized. Table IV presents some of the results of this study. In the case of borax beads more than half of the original material was recovered unfragmented and less than 30% of it was fragmented to less than one-sixth the original size even assuming that the material (27%) lost through the cap wire opening was shattered before hitting these openings, which quite likely is not the case. When quartz was used with RDX, 28% was recovered unfragmented and only 30% was fragmented to less than one-fourth the original size. Unfortunately when larger percentages of explosive were used, it was too difficult to open the cannon owing to binding resulting from detonation against the threaded bolt used to seal the chamber.

In order to test a material of the same particle size and apparent physical texture as the coarse TNT, a shot was made using 15 grams of fine TNT and 40 grams of 4–6 mesh tapioca or ordinary grocery store variety. Examination of the residue showed no evidence of shattering of the tapioca. About one gram of fine material was present which was primarily carbon from the detonated TNT. Although many of the tapioca particles were clumped together by partial fusion at the points of contact, each particle clearly maintained its identity. Tapioca contains considerable moisture as a result of which some of the particles near the center of the chamber swelled and "popped" like popcorn owing to the high temperatures to which they were exposed. Those near the walls of the chamber did not heat and swell, however, apparently because the heat was dissipated with sufficient rapidity through the walls of the cannon to prevent heating of the tapioca grains. The "popping" of the tapioca grains in the interior of the sample was heard to occur up to several seconds after detonation. Of the initial 40 gram sample, 32 grams of material were recovered, the 20% loss being attributed primarily to the loss of moisture.

The difficulty of fragmenting a solid in compression was shown quite convincingly by the following experiment. A charge of liquid nitroglycerine in a 1-in. diameter tube of length/diameter ratio greater than 6 was surrounded by glass marbles in direct contact with the tube of explosive. The charge was then completely surrounded by a heavy wire screen with openings too small to allow the marbles to pass without fragmentation through the wire screen. The basket did not come closer to the explosive charge than 12 in. at any point. This assembly was then placed under water and fired. Most of the marbles were recovered intact. The only effect of exposure to the detonation which should produce a peak pressure in excess of 100 katmos was that the marbles were no longer transparent.

If it is assumed that even as much as half of the coarse TNT was fragmented by detonation before the time that the cannon begins to measure reaction rate, the *p–t* curves observed in this study would still be those determined by the coarse unfragmented fraction, since the peak pressures observed were only about 10–15% lower than those for reaction of fine mesh TNT in which reaction is complete within 50 μsec after the initial detonation. Hence it may be concluded that a large part of the reaction even in the unfragmented portion had taken place at the time corresponding to the peak of the *p–t* curves and that the reaction rates observed were therefore determined by the coarsest fractions. Clearly, therefore, one is dealing with a reaction mechanism even in the after-detonation regime in the cannon experiment which is quite different from the normal pressure sensitive type observed in normal explosive deflagration.

APPENDIX

An evaluation of the accuracy of the numerical method which was used in obtaining the first and second derivatives from the cannon film traces was accomplished as follows. This method of obtaining derivatives was applied to a problem whose derivatives were known, the problem being designed as near in character as possible to the ones encountered in the cannon test. The second derivative was given the form.

$$y''(\lambda)=A\lambda e^{-a\lambda}. \qquad \text{(i)}$$

[A prime indicates differentiation with respect to λ.] It was felt that an exponential form for Eq. (i) would provide a more valid test than a polynomial form, because polynomials were used in the smoothing process. When the parameters (A) and (a) were assigned the values 0.0004 and 0.04 respectively, a curve for $y''(\lambda)$ was obtained which possessed the same general shape as the experimental curves from the cannon experiment and had a maximum of 3.679×10^{-3} for $\lambda=25$. [$\lambda=25$ refers to 25th interval for X_j.]

Integration of Eq. (i) yields for $y'(\lambda)$ and $y(\lambda)$

$$y'(\lambda)=-\frac{A}{a^2}e^{-a\lambda}(a\lambda+1)+y_0', \qquad \text{(ii)}$$

$$y(\lambda)=\frac{A}{a^3}e^{-a\lambda}(a\lambda+2)+y_0'\lambda+y_0. \qquad \text{(iii)}$$

The constant of integration y_0' was given the value A/a^2 and y_0 the value $1-2A/a^3$. In order to simulate the "wiggles" in the film trace caused by the vibration of the slug, a damped sine term was added to Eq. (iii). Equations (iii), (ii), and (i) accordingly may be rewritten

$$\bar{y}(\lambda)=y(\lambda)+Be^{-a\lambda}\sin b\lambda, \qquad \text{(iv)}$$

$$\bar{y}'(\lambda)=y'(\lambda)+Be^{-a\lambda}(b\cos b\lambda-a\sin b\lambda), \qquad \text{(v)}$$

$$\bar{y}''(\lambda)=y''(\lambda)+Be^{-a\lambda}\times[(a^2-b^2)\sin b\lambda-2ab\cos b\lambda]. \qquad \text{(vi)}$$

On the film trace obtained from the cannon experiments the initial amplitude of the "wiggles" was estimated to be less than 0.03 cm, and their maxima were about 4 cm apart or about 10 intervals apart. (Readings were taken on the film at 4 mm intervals.) Thus B was given the value of 0.03 and $b=0.2\pi$ radians.

Values of $y(\lambda)$ were calculated for ($\lambda=0,1,2,\cdots90$) and rounded off at three decimal points. Then these points were smoothed by the IBM, and the first and second derivatives calculated for 1, 2, and 3 smoothings. Figure 8 contains graphs of Eq. (i), Eq. (vi), and values of $y''(\lambda)_1$, the second derivative calculated after one smoothing. Figure 9 contains a graph of Eq. (i), plotted to a different scale than in Fig. 8, and the second derivatives $y''(\lambda)_1$, $y''(\lambda)_2$, and $y''(\lambda)_3$ obtained by the IBM process after 1, 2, and 3 smoothings.

The degree of effectiveness of the smoothing process

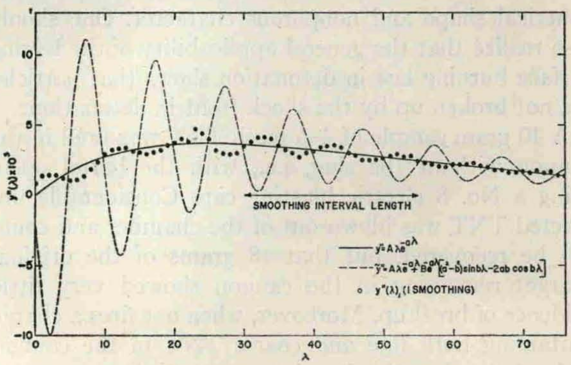

FIG. 8. Comparison of calculated second derivatives with analytical values.