diameter (Mixes 0 and A) reaction is nearly complete at $(dP/d\rho)^{\frac{1}{2}}$ maximum. The steep (somewhat less than proportional) variation of τ with d results from the decrease in the rate of the mixing reaction of the products of decomposition of TNT and AN. Further increase in diameter, from A through B, C, D, and up to E, produces only a slow increase in γ. However, in this range the extent of reaction [up to the maximum $(dP/d\rho)^{\frac{1}{2}}$] decreases considerably. Thus the reaction rate must be decreasing more rapidly with increasing particle size than would be indicated by the increase in reaction time alone. For still larger AN sizes, from E to F and G, the reaction time τ increases strongly with increasing particle size, at a rate which is more than proportional. The estimated energy release indicates that very little of the mixing reaction is occurring in the reaction zone in Mixes F and G. Presumably the decomposition of AN particles, in an atmosphere of the hot products of decomposition of TNT, is the dominant reaction in the neighborhood of $(dP/d\rho)^{\frac{1}{2}}$ maximum. The strong dependence of τ on grain diameter is indicative of a strong dependence of the rate of AN decomposition on grain size.

As discussed above, information on the direct effect of AN particle size on the reaction rate can be obtained by making scale shots. Four such shots, designated A', F', H', and I', were made in which the thickness of the explosive layer and the thickness of the confining plates were reduced by a factor of 0.444. (A' and F' were approximate scale shots of mixes A and F; H' and I' had no corresponding full-size shots.) If the change in AN size produced only a change of time scale of the reaction then at that particle size ratio that changes the reaction time τ by the scale factor the detonation velocity should be unchanged. Shots A and A' gave indentical detonation velocities; and with a particle size ratio of 0.42, compared with the cell size ratio of 0.444, the ratio of reaction times was the same within experimental error. Since reaction is nearly complete, this scaled pair of shots indicates that the reaction time of the "mixing reaction" of the products of decomposition of AN and TNT depends about proportionally on the average diameter of the AN particles under identical conditions of reaction. This finding is in agreement with the results of Eyring, obtained from variation of detonation velocity with charge diameter, on an amatol of somewhat different composition.

Boyer and Grandey[10] calculated the initial transient for a one-dimensional detonation of an explosive consisting of fuel-rich and oxidizer-rich components, using reasonable values of reaction rate constants. They treated the mixing as a laminar diffusion flame. Such a model gives a very strong dependence of reaction time on particle size (r proportional to the square of the particle diameter d). With their reasonable values for the physical constants involved, their calculations indicate that the mixing reaction will contribute substantially to the detonation when the particle diameter is not more than about 10^{-5} cm. Both the magnitude and the linear dependence of r on d found in the amatol experiments indicate that the mixing cannot be occurring by laminar diffusion. Turbulence would tend to make the (eddy) diffusivity proportional to particle size, thus increasing the rate of mixing at larger particle sizes and tending to make the reaction time proportional to d rather than d^2. Turbulent mixing could occur as a result of an appreciable difference in flow velocity between the AN particles and the TNT decomposition products. If the two velocities are the same immediately behind the front then a difference could be set up as reaction releases energy and material into the gas stream. The solid AN particles would tend to lag behind by an amount dependent on the drag of the accelerating gases. By assuming each particle was accelerated by a constant effective drag pressure obtained by using a drag coefficient for spheres of about unity (corresponding to turbulent flow), it was estimated that a difference of velocities of several hundred meters per second could be generated, which is sufficient to give a Reynold's number well into the turbulent range in granular beds even for values of the viscosity coefficient as high as 10^{-2} poises.

In comparing the scale shot designated F' with the $\frac{1}{2}$ in. full-size shots, the AN size ratio which makes the ratio of reaction times equal to the cell size scale (0.444) is about 0.54, corresponding to a full-scale shot lying between E and F at a particle diameter of 0.085 cm (Fig. 10). The detonation velocities (3.17 mm/μsec for F' compared with an interpolated large cell value of about 3.10–3.14 mm/μsec) agree within experimental error. From the estimated amount of energy release in the reaction zone, it is probable that the main energy-releasing reaction at $(dP/d\rho^{\frac{1}{2}}$ maximum is the decomposition of AN. The reaction time for this reaction under identical conditions of reaction is proportional to $d^{4/3}$. A constant linear rate of grain burning would be expected to make τ proportional

[10] M. H. Boyer and R. Grandey, *Detonation and Two-Phase Flow* (Academic Press Inc., New York, 1962), p. 75.

to d. The difference, if significant, may be associated with initiation and forcing of the decomposition of the outer layers of the AN particles.

Indirect methods based on the variation of detonation velocity with charge diameter have not been capable of developing information on the rates of any but the final reaction step when several reaction stages are involved in a detonation. The present direct method can give information on the rates of earlier reaction stages, provided the corresponding energy release is sufficient to maintain the detonation. The small-scale shot I' detonated at a steady velocity of 1.977 mm/μsec and indicated approximately an effective energy release corresponding to that of the TNT alone. The fact that the reaction time curve for the scale shots in the region of large AN particle sizes appears to be flattening indicates that we are approaching the particle size range in which the TNT alone is reacting.

ACKNOWLEDGMENTS

The authors wish to thank D. L. Coursen for his continued encouragement, J. G. Schoppy and J. M. Sandler for assistance in the data reduction, and R. E. Frie, J. E. Hudson, and J. C. Layton for their invaluable help with the experimental arrangements.