# Detonation Wave in Nuclear Explosives

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more than 68 percent oxygen, the intensity was too weak in a single explosion to be of any quantitative value in this problem. Curve $B$ shows that explosions of increasing oxygen content afford greater contrast between the continuous background and the banded structure until the oxygen-CO ratio exceeds 2. It is interesting to note that the best mixture for spectroscopic studies of this combustion is the reverse of stoichiometric mixture; i.e., 2 parts oxygen and one part CO. It is hoped that further studies along this line will permit unambiguous identification of the molecules and radicals present in combustion and will furnish information on the processes involved.

Many investigators have been interested in obtaining OH in absorption in flames for the purpose of determining the concentration of the OH radical. However, in the past it was usually necessary to use the OH emission from a discharge tube in conjunction with a flame. The OH bands can readily be obtained in absorption in the CO-oxygen explosion. The determining factor for obtaining OH in absorption or in emission is the quantity of gas present in the bomb at the time of firing. The explosion of a stoichiometric mixture at one atmosphere pressure will yield OH in absorption, but the same mixture at any pressure less than 0.6 of an atmosphere will produce OH in emission. Figure 2 shows a portion of the OH band at 3064A in
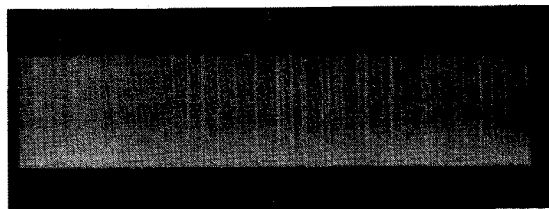


FIG. 2. A portion of OH band at 3064A in absorption obtained on a 21-ft. grating spectrograph.

absorption taken on a 21-ft. grating spectrograph. In addition to the (0−0) OH band at 3064A, the (1−0), (2−0), and the (3−0) bands at 2811, 2609, and 2444A have been observed in absorption in this explosion.

Self-sustaining flames of CO and oxygen with various fuel ratios have been burned in an effort to produce spectra of high contrast but, due to the various degrees of combustion present in a fixed flame, the effect of increased oxygen content is less pronounced than in the explosive flame.

In conclusion I wish to express my appreciation to Dr. B. Lewis, Dr. von Elbe, and Dr. E. F. Fiock for valuable discussions. I am also indebted to Dr. R. C. Herman for helpful suggestions and general encouragement, and to Mr. B. W. Bullock for his assistance in experimental matters. I wish to thank Professor G. H. Dieke for his interest in this problem and for making available to me the 21-ft. Paschen spectrograph at The Johns Hopkins University.

## Detonation Wave in Nuclear Explosives

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IT is known that the hydrothermodynamic theory of detonation developed by Chapman, Jouguet and R. Becker has been used successfully in order to study the detonation of gaseous, liquid and solid explosives.[1] The fundamental equations of the theory can be deduced, for detonation in steady conditions, in a plain and direct way by considering the process from a wholly macroscopic point of view by means of the application of general principles, i.e. laws of conservation of mass, momentum and energy, and the fundamental laws of thermodynamics. Starting from the observation that these principles are valid, independent of the kinetic elementary processes from which the detonation originates, we have thought to apply the hydrothermodynamic theory also in the case in which the explosion is determined by means of a chain process of nuclear fissions, such as that which takes place in a medium of uranium (isotope 235). The explosive material is supposed to occupy a perfectly smooth and rigid cylindrical tube having a sufficiently large diameter so that we consider negligible the effects on the walls of the container; we can also assume that the detonation thus proceeds parallel to the axis of the cylindrical tube. Although this schematization is somewhat different from the conditions realized in practice, nevertheless we believe that it can be used for a rough evaluation of the parameters, which characterize the detonation. In the mathematical theory of the process considered above, it is necessary to keep in mind an essential fact which differentiates the detonations having a nuclear origin from the ordinary ones: in nuclear explosives the temperatures produced are so high, that it is not possible to neglect the effect of the pressure and of the energy of radiation. It is therefore necessary to introduce terms in the equations of the theory taking account of the momentum and energy transferred by the radiation. If the radiation energy density is $E_r$, and the radiation pressure is $p_r = \frac{1}{3}E_r$, the hydrodynamic equations of the ordinary detonation theory shall be replaced by:

$$\rho_1 D = \rho(D - W)$$
$$p_1 + \rho_1 D^2 = (p + p_2) + \rho(D - W)^2,$$
$$\rho_1 D + \rho_1 D[E_1 + (D^2/2)] = (p + p_r)(D - W) + \rho(D - W)$$
$$\times [E + E_r + ((D - W)^2/2)], \quad (1)$$

where $D$ is the velocity of the detonation wave, $W$, the velocity of the explosion products; $\rho_1$, $p_1$, $E_1$ and $\rho$, $p$, $E$ the density, the pressure and the specific internal energy respectively, of the unexploded substance and of the explosion products.

To these equations we shall add the thermodynamic relation

$$E - E_1 = \int_{T_1}^{T} c_v dT - q = \bar{c}_v(T - T_1) - q.$$

The explosion temperatures being extremely high, one can suppose

$$p_r = (aT^4/3) \gg p,$$

calling to mind the well known relation:

$$E_r = aT^4 v$$

and from the preceding equations one deduces, therefore, the Rankine-Hugoniot curve

$$\bar{c}_v(3/a)^{\frac{1}{4}}p^{\frac{1}{4}} + (7/2)pv \cdot (1/2)pv_1 - q = 0$$

where $v = (1/\rho)$, $v_1 = (1/\rho_1)$.

For numerical computations, we observe that the energy liberated from the complete fission of 1 kg $U_{235}$ is

$$q \approx 19.7 \cdot 10^9 \text{ kcal./kg} = 8.4 \cdot 10^{14} \text{ kg} \cdot \text{cm/kg},$$

that the specific heat of the fission products (2 fission nucleus, 2 neutrons, 92 electrons for a single $U_{235}$ atom) can be evaluated considering the mixture as a perfect non-degenerate gas

$$\bar{c}_v = \frac{3}{2}R\frac{96 \times 1000}{235} = 1,21 \text{ kcal./}^\circ\text{K} \cdot \text{kg}$$
$$= 5,18 \cdot 10^4 \text{ kg} \cdot \text{cm/}^\circ\text{K} \cdot \text{kg}.$$

Assuming finally

$$a = 7,81 \cdot 10^{-21} \text{ kg/cm}^2 \text{ }^\circ\text{K}, \quad \rho_1 = 18,7 \text{ kg/cm}^3,$$

Eq. (1) can be written

$$7,25 \cdot 10^9 p^{\frac{1}{4}} + 3,5pv - 26,7p - 8,40 \cdot 10^{14} = 0.$$

Supposing that, as in the case of the ordinary explosions, the stable state of the detonation process is analytically determined by the fact that, corresponding to it, the derivative $ds/dv$ of the entropy must be taken equal to zero, one finds the values

$$p = 9,0 \cdot 10^{12} \text{ kg/cm}^2, \quad v = 30,3 \text{ cm}^3,$$

from which by means of Eq. (1)

$$T = 2,4 \cdot 10^8 \text{ }^\circ\text{K}, \quad D = 3,3 \cdot 10^7 \text{ cm/sec.}, \quad W = 1,4 \cdot 10^7 \text{ cm/sec.}$$

We will finally observe that the value found for the velocity $D$ of the detonation wave is a little smaller than the value $U \approx 2 \cdot 10^8$ cm/sec. or the mean velocity of the neutrons in thermal equilibrium at the temperature $T = 2,4 \cdot 10^8$ °K. The relationship between the velocities $D$ and $U$ is naturally determined by the mechanism from which the chain reaction takes place.

Although the preceding calculations have been established assuming some very rough hypothesis, nevertheless we believe that they can be interesting enough because they suggest a new starting point in order to attack the problem of the detonation of nuclear explosives.

[1] For a review see Stewart Paterson, Research 1, 221 (1948).

## An Equation of State for Gases at Extremely High Temperatures and Pressures From the Hydrodynamic Theory of Detonation

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I HAVE read the reply[1] of M. A. Cook to my criticisms[2] of his paper,[3] and realize that I was mistaken in supposing that he regarded his first method of solution as in practice more "general" than the second. As a matter of fact, I was more concerned with his claim that such a general solution was possible even in principle. Unfortunately, I can find no ground in his reply for revising my arguments regarding either this question or the detailed method of solution, but since these arguments have already been stated it seems unprofitable merely to repeat them.

My further point regarding the method of successive approximations as compared with step-by-step integration along an $\alpha(v_2)$ curve was largely mathematical. $\alpha$ is of course "well-defined," but it is a question here of determining it by the solution of certain equations. If one proceeds by a stepwise method from an assumed point in the $(v_2, \alpha)$ plane lying below Cook's curve, one does in fact derive two members of an integral family, of which Cook's curve is the envelope. This is just what one would expect on mathematical grounds. For various *physical* reasons, including that offered by Cook, it can be judged that these integral curves are on the whole unacceptable, but this did not appear to me to dispose of all interest attached to the question.

[1] M. A. Cook, J. Chem. Phys. 16, 554 (1948).
[2] S. Paterson, J. Chem. Phys. 16, 159 (1948).
[3] M. A. Cook, J. Chem. Phys. 15, 518 (1947).

## Testing of Colloidal Solutions by Dye Solubilization

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EXTENSIVE studies by McBain and collaborators[1-3] have elucidated dye solubilization phenomena which, in turn, gave valuable information on the structure of colloidal micelles. In some of their publications[2,4,5] solubilization data are given for commercial surface-active agents with the implication that dye solubilization is useful in evaluating the relative efficiency of such compounds. The experimental procedure which has been used at the Stanford Laboratory appears rather tedious since it involves the attainment of equilibrium conditions requiring periods in the order of days or even weeks.