NATIONAL BUREAU OF STANDARDS REPORT

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THERMAL RADIATION FROM HIGH EXPLOSIVES AT REDUCED PRESSURE

by

W. Fussell and J. Geist
Photometry and Colorimetry Section
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NBS

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ABSTRACT

A semi-empirical formula has been developed to fit the data of Cavanagh and Rockman on thermal radiation from 2 oz charges of high explosive at sea-level and at pressures of 72.5, 7.0, and 6.5 mm of Hg. The formula is based on the point-source model of Taylor and the mathematical development of Bethe. The formula indicates that the thermal radiation from a high-explosive charge varies inversely as the atmospheric density and is proportional to the 3.5 power of the total explosion energy, which is taken as the heat of combustion if the explosion occurs in a chamber containing more than sufficient oxygen to completely burn the explosive; the total explosion energy is taken as the heat of detonation if there is insufficient oxygen to burn the explosive.

INTRODUCTION

In 1960, Cavanagh and Rockman[1] published the results of experimental measurements of the thermal radiation from 56.7 gm (2 oz.) charges of high explosive (Pentolite) detonated in a vacuum chamber at pressures of 760 (sea-level), 72.4, 7.0, and 6.5 mm of Hg. Figure 1 presents their data for the total thermal radiation emitted by the explosive charges as a function of the initial pressure in the vacuum chamber. The large increase in total thermal radiation as the initial chamber pressure is reduced from 760 to 72.5 mm of Hg is particularly striking, as is the fact that the ratio of the total thermal radiation yields is very nearly equal to the *reciprocal* of the ratio of the initial pressures. As the initial chamber pressure is reduced still further, however, to 7.0 mm of Hg, the total thermal radiation *drops* by a factor of roughly two. A clue to this behavior is provided by the work of Filler[2] who has shown that the total heat energy produced by many explosives (including Pentolite) is much larger when the explosive is detonated in air at sea-level initial pressure than when the explosive is detonated in a *nitrogen* atmosphere. The difference in energy output is due to *burning* of the explosive in the oxygen of the air. When an explosive is detonated in the presence of a larger than stoichiometric amount of oxygen, the heat energy output is the "heat of combustion "(H. C.); when the explosive is detonated in nitrogen (presumably detonation in a vacuum produces the same result), the heat energy output is the "heat of detonation" (H. D.). Pentolite has an H. C. of 2500 cal gm^{-1} and an H. D. of 1100 cal gm^{-1}.

The next step is to develop a mathematical model of an explosion which will allow the total thermal radiation to be computed. The work of Taylor[3] and Bethe[4] provides the basis for the model.

THEORY

If one assumes the explosion to take the form of an isothermal, expanding spherical shell of emissivity one, the equation for the total thermal radiation from the explosion E_{RAD} can be written as

$$E_{RAD} = \int_{Y_o}^{\infty} 4\pi\sigma \, Y^2 T^4 \dot{Y}^{-1} \, dY \quad , \qquad (1)$$

where Y is the radius of the spherical shell,

σ is the Stefan-Boltzmann constant

T is the temperature of the spherical shell,

Y_o is the initial radius of the shell, and

$\dot{Y}$ is the radial velocity of the shell (the dot over the quantity signifies differentiation with respect to time).

Now the total kinetic energy E_{KIN} of the expanding spherical shell is obviously

$$E_{KIN} = \left[4\pi\, 3^{-1}\, \rho(Y^3 - Y_o^3) + M_o\right] 2^{-1}\dot{Y}^2 \quad , \qquad (2)$$

where ρ is the density of the undisturbed air, and

M_o is the mass of the explosive.

Bethe[4/] shows that E_{KIN} is related to the total explosion energy E_{TOT} by the equation

$$E_{TOT} = E_{KIN}\left[(\gamma - 1)^{-1} + 0.807\right] \quad ; \qquad (3)$$

γ is approximately the ratio of the specific heats at constant pressure and volume of the surrounding air (γ is 1.4 for air at room temperature and normal atmospheric pressure).

Next $\dot{Y}^{-1}$ can be expressed in terms of Y, Y_o, ρ, M_o, E_{TOT}, and γ, by use of Eqs. (2) and (3), as

$$\dot{Y}^{-1} = E_{TOT}^{-1}\left[(\gamma - 1)^{-1} + 0.807\right]\left[4\pi 3^{-1}\rho(Y^3 - Y_o^3) + M_o\right] 2^{-1} \quad {}^{0.5} \quad . \qquad (4)$$

To express T as a function of Y, it is assumed that T varies inversely as the sum of M_o and the mass of the air, M_A, swept up in the expanding spherical shell, that is

$$T\, T_o^{-1} = \left[1 + 4\pi 3^{-1}\, M_o^{-1}\, \rho(Y^3 - Y_o^3)\right]^{-1} \quad , \qquad (5)$$

where T_o is the initial explosion temperature.

To relate T_o to E_{TOT}, it is assumed that T_o is proportional to E_{TOT}, that is

$$T_o = C_v^{-1}\, E_{TOT}\, M_o^{-1} \quad , \qquad (6)$$

C_v is a constant having the dimensions of a specific heat.

If the values of $\dot{Y}^{-1}$, T, and T_o, from Eqs. (4), (5), and (6), respectively, are substituted in Eq. (1), E_{RAD} is found to be given, for infinite Y, by

$$E_{RAD}\, M_o^{-1} = \sigma\, C_v^{-4} A^{0.5}\, 0.4\, (E_{TOT}\, M_o^{-1})^{3.5}\, \rho^{-1} \quad , \qquad (7)$$

where $A \doteq 0.5\left[(\gamma - 1)^{-1} + 0.807\right]$.

It is clear from Eq. (7) that E_{RAD} is inversely proportional to the initial density of the air in the vacuum chamber, and is proportional to the 3.5 power of the explosion energy.

It is now further assumed that the total explosion energy is given by the H. C. when the vacuum chamber contains more than sufficient oxygen to completely burn the explosive, and is given by the H. D. when the amount of oxygen in the chamber is much less than stoichiometric.

COMPARISON OF THEORY AND EXPERIMENTAL DATA

Filler[2/] gives the H. C. of Pentolite as 2500 cal gm^{-1} and the H. D. as 1100 cal gm^{-1}. Filler's vacuum chamber was used by Cavanagh and Rockman for their experiments; it had a volume of 2050 liters. At S. T. P. this volume of air contains 613 gm of O_2. Take the charge weight M_o as an even 57 gm; then if it is assumed that the combustion of Pentolite simply burns H to H_2O and C to CO_2, it can be shown that 57 gm of Pentolite requires approximately 32 gm of atmospheric O_2 for complete combustion. Furthermore, even at a vacuum chamber pressure of 72.5 mm of Hg, the chamber still contains about 58 gm of O_2 which is more than the stoichiometric amount (32 gm) required for complete combustion. At a pressure of 7.0 mm of Hg in the vacuum chamber, however, the amount of O_2 in the chamber is only 5.6 gm, much less than the stoichiometric quantity.

It seems reasonable, therefore, to use the H. C. of Pentolite in computing the total explosion energy E_{TOT} for chamber pressures of 72.5 mm of Hg or higher, while the H. D. of pentolite is used for chamber pressures of 7.0 mm of Hg or lower. If this procedure is followed in computing the total radiated energy E_{RAD} by Eq.(7) and if the values of the constants A and C_v in Eq. (7) are taken to make the computed E_{RAD} agree with the experimental value of E_{RAD} at normal atmospheric pressure, then Table I and Fig. 1 show that the computed values of E_{RAD} at pressures of 72.5, 7.0, and 6.5 mm of Hg fall within about 15% of the experimental values of Cavanagh and Rockman.

Furthermore, if the ratio of the specific heats, γ, is taken as 1.4, σ as 0.567×10^{-11} watt cm^{-2} $(°K)^{-4}$ [5/], and the atmospheric density as 1.292×10^{-3} gm cm^{-3} [6/] (0°C), the value of the initial explosion shock front temperature T_o can be computed by substituting Eq. (6) into Eq.(7) and using the experimentally measured value for E_{RAD} as given in Table I. This computed value of T_o is about 8,100°K, which agrees in order of magnitude with Brode's[7/] computer calculation of 11,000°K for the initial shock front temperature for a TNT explosion in air at sea-level. (TNT has a much higher H. C. than Pentolite, 3220[2/] cal gm^{-1}. It is interesting that the ratio of 11,000 to 8,100 is roughly equal to the ratio of

the H. C. of TNT to the H. C. of Pentolite.)

CONCLUSIONS

The formula derived in this paper gives the total thermal energy radiated by a high-explosive charge as a function of the total explosion energy, the atmospheric density, and other quantities. The formula appears to be useful on the basis of the very limited amount of data available. Much more experimental data is required to establish the validity of the formula with any certainty.

The theoretical justification of the formula is tenuous and the formula at this time should be regarded as semi-empirical. In particular, the mathematical procedure of letting the shock front radius Y become infinite to derive Eq. (7) is an *ad hoc* stratagem applied to fit the experimental data.

TABLE I.

Experimental and computed values of the total thermal energy radiated by high-explosive charges detonated in a vacuum chamber at sea-level and reduced pressure.

Pressure, (mm of Hg)	Thermal Yield, Exptl., no lens[a] (cal)	Thermal Yield, Exptl., with lens[a] (cal)	Thermal Yield, Computed[b] (cal)
760	4.49×10^2	4.40×10^2	4.40×10^2
72.5	5.23×10^3	4.57×10^3	4.61×10^3
7.0	2.48×10^3	2.32×10^3	2.70×10^3
6.5	3.01×10^3	No Data	2.91×10^3

[a] Cavanagh and Rockman used a lens to limit the field of view of their radiation detector in some of their measurements.

[b] The computed data are normalized to the experimental value of the thermal yield *with* a lens at 760 mm of Hg.

FIGURES

1. Experimental and computed values of the total thermal radiation from 57 gm Pentolite charges as a function of pressure.

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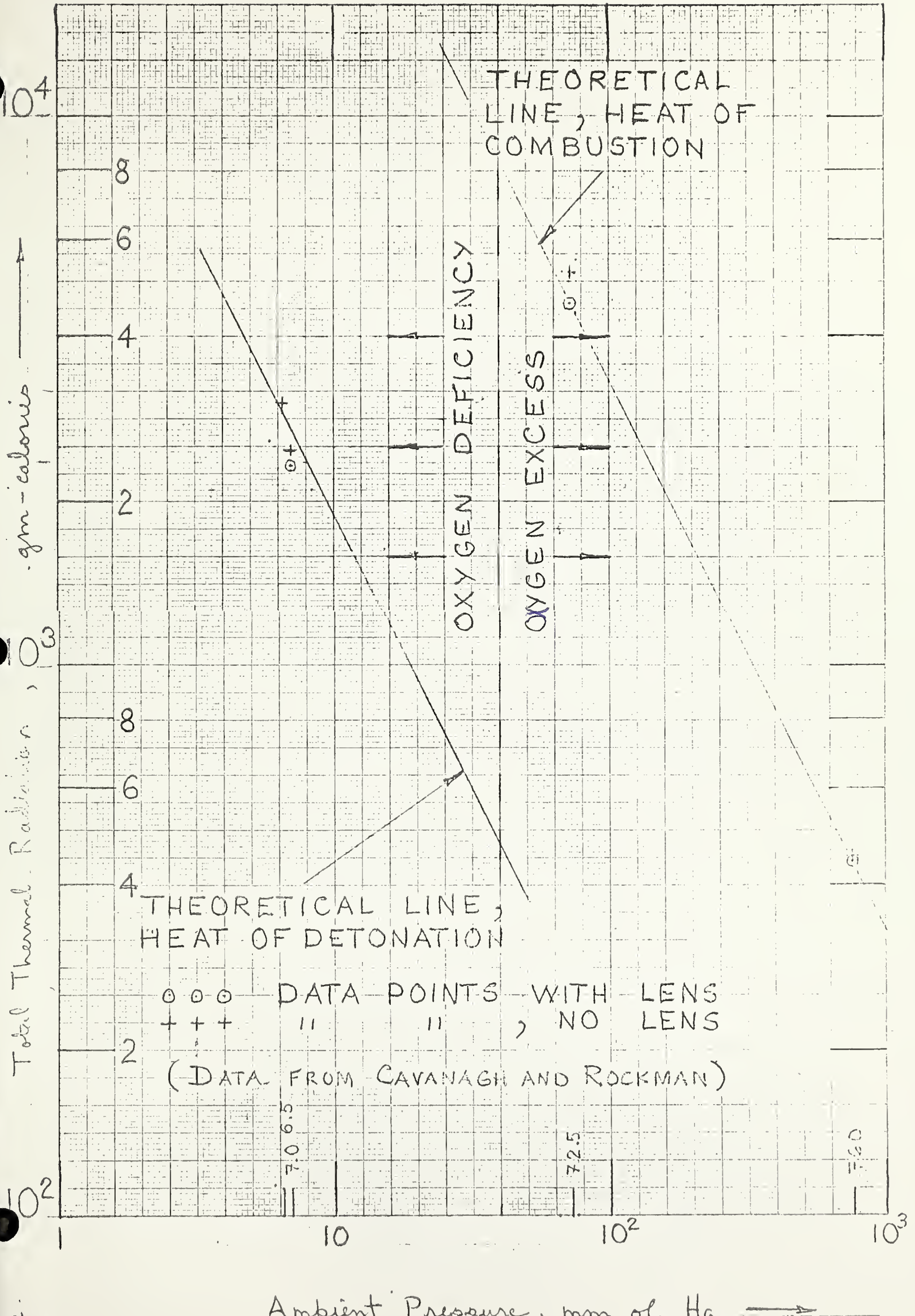
THEORETICAL LINE, HEAT OF COMBUSTION
OXYGEN DEFICIENCY
OXYGEN EXCESS
THEORETICAL LINE, HEAT OF DETONATION
○ ○ ○ DATA POINTS WITH LENS
+ + + " " , NO LENS
(DATA FROM CAVANAGH AND ROCKMAN)
7.0 6.5
72.5
760
10⁴
8
6
4
2
10³
8
6
4
2
10²
1
10
10²
10³
Total Thermal Radiation, gm-calories →
Ambient Pressure, mm of Hg →

Fig. 1


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