

Use of an ElectroOptical Method to Determine Detonation Temperatures in High Explosives

F. C. Gibson, M. L. Bowser, C. R. Summers, F. H. Scott, and C. M. Mason

Citation: *J. Appl. Phys.* **29**, 628 (1958); doi: 10.1063/1.1723242

View online: <http://dx.doi.org/10.1063/1.1723242>

View Table of Contents: <http://jap.aip.org/resource/1/JAPIAU/v29/i4>

Published by the [AIP Publishing LLC](#).

Additional information on J. Appl. Phys.

Journal Homepage: <http://jap.aip.org/>

Journal Information: http://jap.aip.org/about/about_the_journal

Top downloads: http://jap.aip.org/features/most_downloaded

Information for Authors: <http://jap.aip.org/authors>

ADVERTISEMENT



The advertisement banner features a green and yellow background with abstract wavy lines. On the left, the text 'AIPAdvances' is displayed in a stylized font, with 'AIP' in blue and 'Advances' in green, followed by a series of orange dots. On the right, a circular seal contains the text 'Now Indexed in Thomson Reuters Databases'. Below this, a blue bar contains the text 'Explore AIP's open access journal:' followed by a bulleted list of features.

AIPAdvances

Now Indexed in
Thomson Reuters
Databases

Explore AIP's open access journal:

- Rapid publication
- Article-level metrics
- Post-publication rating and commenting

Use of an Electro-Optical Method to Determine Detonation Temperatures in High Explosives*

F. C. GIBSON, M. L. BOWSER, C. R. SUMMERS, F. H. SCOTT, AND C. M. MASON

Bureau of Mines, U. S. Department of the Interior, Division of Explosives Technology, Pittsburgh, Pennsylvania

(Received October 30, 1957)

A method has been devised for sampling the optical radiation from the interior of a detonating solid-explosive charge by introducing a transparent plastic rod axially into the charge at the time of fabrication. The radiation was analyzed by a grating spectrograph, using four bands 100 Å wide and 600 Å apart. The radiation intensities were used to calculate the color temperatures within the detonating explosive. The apparatus was calibrated by a radio-frequency-excited lamp known to have gray-body radiation. The explosive charges were vacuum-impregnated with propane to replace the air in the intergranular voids to eliminate light emission from the air shock.

INTRODUCTION

THE temperature in the detonation front has been one of the variables most urgently needed in the field of solid-explosive research. Although measurement of this variable has been a matter of active interest for some time,¹ the experimental determination of definitive temperatures has not been reported in the open literature.

One method of remote measurement of the temperature in the detonation front of a solid explosive, which seemed to offer promise, is the two-color method in which the quality of the emitted radiation is evaluated by a multiplier phototube color pyrometer.² The novel aspect of the present technique employed in the application of this method is in the means of radiation sampling. A cylindrical polymethyl methacrylate probe, introduced into the explosive charge during fabrication, "pipes" the radiation from within the charge into the optical system of the sensing equipment. Since the rod probe extends axially into the end of the charge, the radiation source is from a zone of high confinement and should be characteristic of the "infinite" slab and representative of steady-state conditions within the charge near the core. Also, an important consequence of this technique is the radiation burst which persists for several microseconds during the passage time of the detonation zone along the rod; this reduces the response requirements of the electronic recording system to practical limits.

Our first color pyrometer used two channels with the wavelength and width of the channels determined by optical filters. Due to the shape of the transmission-frequency curves of the filters, it was necessary to calibrate the apparatus in the region of expected temperatures; this did not prove feasible, and after a few preliminary measurements this technique was abandoned.

* This work was reported at the 1957 Annual Meeting of the American Physical Society in New York, New York.

¹ S. J. Jacobs, *Phys. Rev.* **72**, 176 (1947).

² Russell, Lucks, and Turnbull, "A New Two-color Optical Pyrometer," *Temperature: Its Measurement and Control in Science and Industry* (Reinhold Publishing Corporation, New York, 1941), p. 1159.

By using a grating spectrograph as a monochromator for each band, it was possible to calibrate the system at a convenient low temperature and extrapolate to higher temperatures; this technique was adapted for the experiments to be described.

THEORY

The method used for measuring detonation temperatures is based on the energy distribution of the radiation emitted from the detonating explosive. According to Wien's law, the energy radiated by a black body at temperature T at any wavelength λ in a band of width $\Delta\lambda$ is

$$E_\lambda = c_1 \lambda^{-5} e^{-c_2/\lambda T} \Delta\lambda. \quad (1)$$

However, if two channels are employed, it is unnecessary to measure absolute energies since a ratio will suffice; thus,

$$\ln \frac{E_1}{E_2} = -5 \ln \frac{\lambda_1}{\lambda_2} - \frac{c_2}{T} \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) + \ln \frac{\Delta\lambda_1}{\Delta\lambda_2}. \quad (2)$$

Equation (2) may be converted to common logarithms and written in the form

$$\log(E_1/E_2) = A + B(1/T). \quad (3)$$

Here constant "B" is a function of the wavelengths used and can be found from the constants of the apparatus, while constant "A" may be determined by measuring ratio E_1/E_2 of a black or gray body at a known temperature.

In practice, neither the absolute energies nor their ratio is determined directly. Instead, the radiation of a particular wavelength falls on a multiplier-type phototube, and the voltage developed across its load resistor is measured by a cathode-ray oscillograph. The deflection of the cathode-ray oscillograph is then proportional to E ,

$$D = kE; \quad (4)$$

replacing E in (3) with D/k yields

$$\log(D_1/D_2) = \log(k_1/k_2) + A + B(1/T) \quad (5)$$

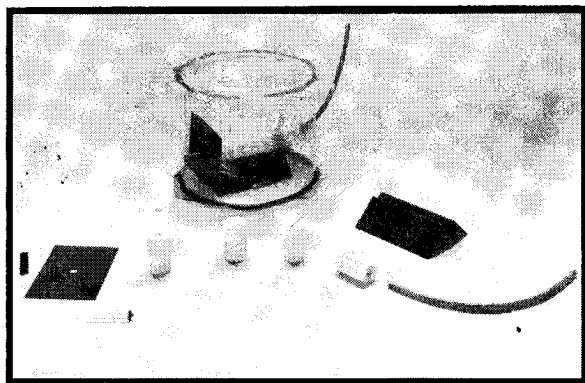


FIG. 1. Components used in a typical high-density charge for detonation temperature determinations and a completed charge ready for firing.

and combining constants

$$\log(D_1/D_2) = A' + B(1/T). \quad (6)$$

Equation (6) is used to calibrate the apparatus and to determine the temperature of detonation.

EXPERIMENTAL

The construction of a typical high-density charge and a completed assembly is shown in Fig. 1. The components include the plastic rod with an opaque end, the surrounding charge, two booster pellets of identical density and material, the oscillograph sweep synchronizing station, a tetryl booster, a detonating fuse, and the support stand and container. The rod probe was introduced into pelleted-type charges for loading densities above 1.2 g/cm^3 at the time of fabrication with a Stokes³ tableting machine; this resulted in a close fit between the rod and the explosive material. Charges under 1.2 g/cm^3 were hand-packed into 1-in. i.d. rigid plastic tubes having a wall thickness of $\frac{1}{8}$ -in. Rods for both type charges were machined from cast slabs of Plexiglas⁴ UVA II stock. All rods used were 6 mm in diameter and extended about 2 cm into the charge. The inner end of the rods were machined to a cone to permit explosive powder flow around the rod end during filling and pressing. Maximum densities were limited to about 1.58 g/cm^3 since the use of greater press pressures required for higher densities resulted in pellet cracking. The conical rod end was coated with opaque black lacquer to limit radiation pickup during the passage of the detonation zone over the rod end. This was necessary, since the optical transmission with end-on pickup is apparently much greater than with side pickup. Omission of an opaque coating caused serious overload of the electronic circuits.

Early experimentation indicated that it would be necessary to vacuum-impregnate the granular charges with, and fire them in, a gas having a low ratio of

³ F. J. Stokes Machine Company, Philadelphia 20, Pennsylvania.

⁴ Trademark of Rohm & Haas.

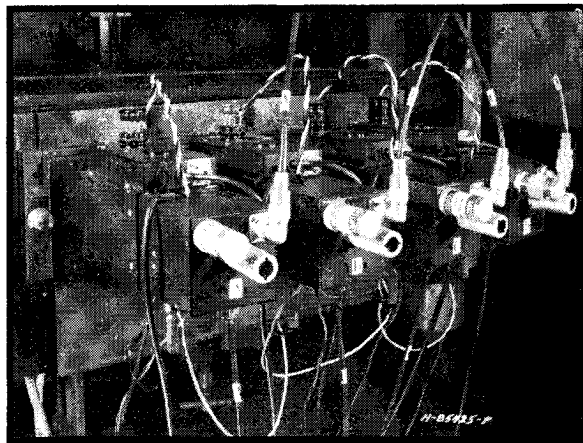


FIG. 2. The multiplier phototube receiver, showing the housings and cathode followers in place on the spectrograph plate holder.

specific heats (gamma). Temperatures obtained from low-density charges in which the impregnation was omitted were high (compared to impregnated charges) by a factor of two or three. The difference in indicated temperatures became less at higher densities; near crystal density impregnation had little effect. All charges were identically processed by three cycles of evacuation and impregnation with propane. The charge was placed in a cellulose acetate container which maintained the ambient atmosphere of propane in and around the charge during firing; this is shown in the background in Fig. 1. Storage and handling were facilitated by the use of glass desiccators.

An ionic conduction probe was introduced into the charge to provide synchronization of the oscillograph sweep to the detonation. An opaque paper baffle and sleeve were placed over the portion of the rod which protruded from the charge to prevent admission of unwanted background radiation into the system.

An image of the plastic rod end was focused on a modified entrance aperture of a 21-ft Jarrell-Ash spectrograph. The entrance slit was replaced by a circular hole about 2 mm in diameter, which admitted the radiation from the entire rod end. A 15 000-line/inch concave grating was used, giving a dispersion of 5 Å/mm. The spectrograph was modified further by replacing the photographic plate holder with a multiple exit-aperture plate. The exit apertures were positioned so that the entire photographic plate width was used to provide maximum physical separation for four channels. A DuMont Type 6292 multiplier phototube was placed behind each of the exit slits; tubes were selected to provide maximum response for the wavelengths employed. A photograph of the receivers in place on the plate holder of the spectrograph is shown in Fig. 2. The receivers are placed about 600 Å apart and are centered on the following center frequencies for each wavelength band of approximately 100 Å width: 6081 Å, 5461 Å, 4843 Å, and 4223 Å. The 5461 Å

(mercury-green line) channel was used as the reference for the accurate adjustment of the plate holder position. All tubes were optically and magnetically shielded. The output of each phototube was coupled through a cathode follower and a low-impedance line to a Tektronix Type 535 cathode-ray oscilloscope employing the wide-band, high-gain, 53B preamplifier. The over-all frequency response of the electronic system is uniform to about 10 Mc with a linear vertical deflection of 6 cm. Oscillograph traces were recorded photographically with DuMont-Polaroid cameras having $f/1.9$ lenses and using either Pola-Pan 400 film or Eastman Royal-Pan film in special camera backs constructed to fit the DuMont camera.

CALIBRATION

Dynamic calibration of the apparatus was made before each test. This furnished a continual check on the apparatus for any calibration shift that might have been caused by the physical violence of the previous explosive test, as well as that from normal component aging or failure. Temperature calibration consisted of admitting radiation from a source of known temperature and emissivity into the system. This source was the target of a radio-frequency-excited lamp.⁵ The lamp consists of a $\frac{5}{16}$ -in. tantalum carbide disk supported in a water-cooled field concentrator by a zirconium oxide rod; this assembly is contained in an argon-filled glass envelope at a pressure of 2 atmos. The lamp is placed in the water-cooled work coil of a 1.5-kw radio-frequency generator operating at approximately 3.5 Mc. An image of the radiation source ($\frac{5}{16}$ -in. disk) was formed on the spectrograph entrance aperture, so that only radiation from the temperature-gradient-free center zone passed into the spectrograph. A front surface mirror allowed the calibration lamp system to be placed in the instrument room. A motor-driven light chopper, having a narrow slit in the periphery, interrupted the radiation into approximately 50- μ sec pulses, and a photoelectric synchronizer permitted the sweep to be triggered before each pulse.

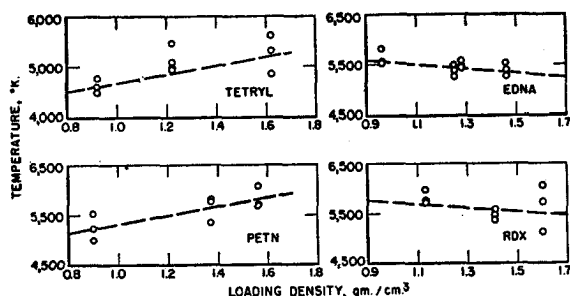


FIG. 3. Graphical representation of the temperature-density relationship for four pure compound explosives where each point is the average of six two-channel combinations for a single test.

⁵ Type AN-20 manufactured by Sylvania Electric Products, Salem, Massachusetts.

Since the slope of the calibration is established by the wavelength bands for each color pair combination, only the intercept needed to be experimentally established. For this purpose, the lamp was operated in the region of 2800°K; checks were made on the fit of four calibration lamp temperatures (2770°K, 2640°K, 2480°K, and 2310°K) for the six-channel combinations. The maximum deviation was 50°K.

The rf lamp temperatures were determined during the calibration period with a disappearing-filament

TABLE I. Temperatures of detonation as determined by an electro-optical method. The temperature reported for each test represents the average of six temperatures obtained by the six possible pair combinations when using four wavelengths. All charges were propane impregnated.

Density, g/cm ³	Temperature, °K	Density, g/cm ³	Temperature, °K
PETN		RDX	
0.90	5525 5225 5000	1.13	5715 5970 5742
1.37	5762 5756 5343	1.41	5367 5462 5577
1.56	6079 5684 5705	1.60	6056 5734 5136
Tetryl		EDNA	
0.92	4479 4750 4600	0.96	5819 5525 5547
1.22	5464 4975 4940 5093	1.25	5241 5368 5485
1.62	5619 4837 5297	1.28	5437 5430 5585
		1.46	5526 5263 5375
		Nitroglycerin	
		1.60	3896 4095 4079

optical pyrometer and converted to the true temperature by application of an emissivity for tungsten carbide of 0.55 at a wavelength of 6600 Å and a temperature of 2500°C.⁶ The optical pyrometer was standardized on a tungsten ribbon lamp, which had been certified by the General Electric Company, Nela Park Lamp Works, Cleveland, Ohio.

⁶ J. d'Ans and E. Lax, *Taschenbuch für Chemiker und Physiker* (Springer-Verlag, Berlin, 1943).

RESULTS

The observed detonation temperatures vs loading density obtained with the spectrographic method for PETN, tetryl, RDX, and EDNA are shown graphically in Fig. 3 and given in Table I, where each temperature is the average of six temperatures obtained from the six possible pair combinations using four wavelength channels. Table I also gives the detonation temperature of nitroglycerin viewed end on, without rods. The average deviation from the means for each explosive material is 180°K for PETN; 180°K for tetryl; 173°K for RDX; 92°K for EDNA; and 85°K for nitroglycerin. Table II presents the detonation temperatures for a single permissible explosive material in two diameters. The explosive was composed of the following ingredients: ammonium nitrate 67.8%, sodium nitrate 14.1%, explosive oil 9.1%, carbonaceous combustible material 7.3%, and minor ingredients 1.7%. The explosive was tested as received in the original wax-coated wrapper and was initiated by a tetryl booster.

TABLE II. Temperatures of detonation determined by the electro-optical method for a permissible explosive (6 tests). The density of the charge was 1.05 g/cm³, and the average velocity of detonation from the luminosity-time oscillogram was 1793 m/sec. The charge was impregnated and fired in ambient propane.

Diameter, inches	Temperature, °K
1½	2596
	2685
	2696
1¼	2615
	2685
	2724

The rod probe was inserted into the loose powder, and the standard procedure of gas impregnation was used. A dry ice-alcohol trap was installed in the vacuum line to condense any explosive oils (nitroglycerin and nitroglycol) that were vaporized. A trace of these oils which appeared in the trap were evident only after the propane, which had been liquefied in the trap, boiled off. Velocities of detonation were obtained from the luminosity-time oscillograms and were in good agreement with observation from routine tests. The average deviation from the mean is 40°K, and the temperature results are independent of the diameter.

Radiation-energy distribution relative to the energy of the 5461 Å channel for tests on RDX (1.60 g/cm³), tetryl (0.92 g/cm³), and nitroglycerin are shown graphically in Fig. 4. A black-body curve is constructed through the reference channel, and the experimentally determined points are plotted; good distribution agreement is shown. The data on the granular materials were obtained by the probe method, and the data on the liquid explosive were accumulated without probes by looking into the charge end on through the un-

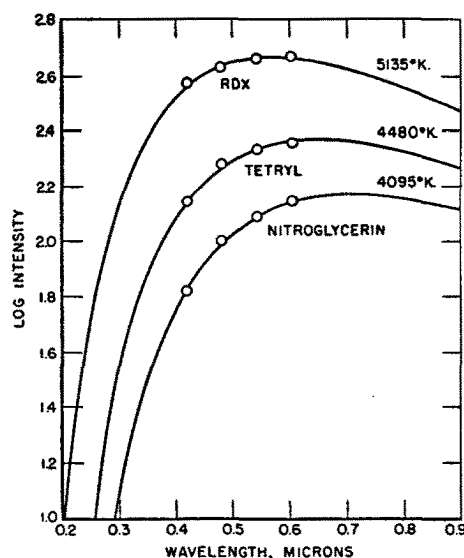


FIG. 4. Radiation distribution curves for a liquid (nitroglycerin), a low-density granular (0.92 g/cm³ tetryl), and a high-density granular (1.60 g/cm³ RDX) explosive. A blackbody curve is constructed through the reference intensity level at 0.55 μ for each explosive test.

detonated transparent explosive. However, tests conducted using the optical filter method on nitroglycerin, both with and without rods, gave temperature-data agreement, with a standard deviation of 10°K.

The detonation temperature of nitroglycerin was found to be 4000°K by both the earlier optical filter and the spectrographic methods for high-order detonation (verified by velocities of about 7500 m/sec obtained from the radiation-time characteristics of the temperature oscillograms). Initiation of nitroglycerin by weak mercury fulminate-potassium chlorate detonators produced temperatures of approximately 3200°K for the low-detonation-velocity regime of 1500 to 2000 m/sec. The low order of detonation was substantiated by examination of a lead block on which the charge rested during the temperature test.

A temperature of 3800°K for detonating nitromethane was determined by the optical filter method. Care was taken in these tests to assure near-ideal predetonation conditions of high ambient temperature, adequate charge diameter, and sufficiently strong initiation.

Several forms of equations of state for gases at very high densities and temperatures exist, none of which are accepted by everyone concerned as being completely valid. Since the hydrodynamic theory of detonation relates the pressure, temperature, density, streaming velocity, and wave velocity to the detonating system and the equation of state of the products, physical measurement of several of these variables is necessary to completely test the validity of any equation of state. Of these properties, the temperature is the most sensitive to the assumptions made. No single equation of

state is validated by the data presented in this paper; however, orders of magnitude for the solid explosives favor the theories of Cook,⁷ Caldirola,⁸ and Paterson⁹ until more recently, when the latter and Cottrell¹⁰ considered intermolecular repulsive forces. On the other hand, the temperatures obtained for nitroglycerin agree well with the theory of repulsive intermolecular potential of Hikita and Kihara.¹¹ These data are

⁷ M. A. Cook, *J. Chem. Phys.* **15**, 518 (1947).

⁸ P. Caldirola, *J. Chem. Phys.* **14**, 738 (1946).

⁹ S. Paterson, *Research I*, 221 (1948).

¹⁰ T. L. Cottrell and S. Paterson, *Proc. Roy. Soc. (London)* **A213**, 214 (1952).

¹¹ T. Hikita and T. Kihara, *Fourth International Symposium on*

presented in the anticipation that application of them will be made to future theoretical studies.

ACKNOWLEDGMENTS

This project was supported by the Office of the Chief of Ordnance, Department of the Army, Army Project 504-01-015, Ordnance Corps Project TA3-5101. This work was under the technical supervision of the Physical Research Section, Samuel Feltman Laboratories, Picatinny Arsenal.

Combustion (Williams and Wilkins Company, Baltimore, 1953), p. 458.

Analysis of a Multipole State Separator and Focuser for Polarizable Molecules

FRIEDRICH O. VONBUN

U. S. Army Signal Engineering Laboratories, Fort Monmouth, New Jersey

(Received August 29, 1957)

The electrostatic field of a multipole focuser, consisting of parallel rods arranged in a circle, is treated. The field equation is derived from the known field of a two-wire line, and results are given in the form of equations that express the field in terms of practical parameters. The field and the radial gradient of a $(p+q)$ -pole focuser is compared to that of a p -pole focuser in order to indicate the value of increasing the number of poles.

Both a complete and a simplified set of differential equations (in cylindrical coordinates) of the path of polarizable molecules in this inhomogeneous field are also given. Based on the simplified differential equations, the path of a NH_3 molecule in the $J=K=3$ ($M_J=3$) inversion state is graphically presented.

1. INTRODUCTION

IN this paper, a device is described which is used to select and, at the same time, focus¹ molecules in certain quantum states from a beam of molecules in thermal equilibrium. The focuser consists of an even number p of alternately charged parallel rods, equally spaced to form a cylinder whose length is large compared to the mean diameter of the assembly (see Fig. 1). Such a focuser is used, for instance, in the ammonia maser,²⁻⁴ which is a device utilizing a molecular beam, in which molecules in the excited state of a microwave transition are selected and then directed into a microwave cavity. Interaction between these excited molecules and a microwave field produces oscillation under certain conditions.

The word "focuser" is not to be understood in the optical sense. That is, molecules starting at the entrance of this device with the same position, r_0 , φ_0 , but with different velocities, v_0 , and directions θ_0 (the angle between v_0 and focuser axis) do not converge to one point at the end of the focuser. The optical focusing condition, namely, that $r(t)$ follows a linear homoge-

neous second-order differential equation,⁵ as in the case of an electronic lens near the axis, does not hold here.

The focusing and separation action of a focuser can be understood best by considering, for instance, the equation for the Stark energy² of NH_3 in high fields $W=W(E)=W_0 \pm [(h\nu_0/2)^2 + \mu_{12}^2 E^2]^{\frac{1}{2}}$. Since the force acting on a molecule is $f = -\text{grad}W(E)$, one can see that this force has two possible signs, depending upon the energy state of the molecule under consideration. If we arrange the magnitude of the electric field in this focuser to increase with increasing distance from its axis, then the molecule in the higher energy state (+square root) will be directed toward the axis. In the following pages it will be shown that this is the case for the particular focuser construction described.

The sign of the slope, $\partial W/\partial E$, of a diatomic molecule, such as NaCl ⁶⁻⁸ depends on the magnitude of the electric field as well as on its state of energy. Even in

⁵ W. Glaser, *Grundlagen der Elektronenoptik* (Springer-Verlag, Vienna, 1952).

⁶ A. Honig *et al.*, *Phys. Rev.* **96**, 629 (1954).

⁷ USASEL contract with Varian Associates: "Research on Molecular and Atomic Resonance Devices," DA36-039 SC-72398, Quarterly Report No. 1 (1956).

⁸ M. Strandberg and M. Peter, "Molecular-Beam Microwave Spectroscopy," USASEL contract with Massachusetts Institute of Technology, DA36-039 SC-73014, Quarterly Report, October 15, 1956.

¹ Bennewitz, Paul, and Schlier, *Z. Physik* **141**, 6-15 (1955).

² Gordon, Zeiger, and Townes, *Phys. Rev.* **99**, 1264 (1955).

³ Shimoda, Wang, and Townes, *Phys. Rev.* **102**, 1308 (1956).

⁴ N. Basov, *Radiotekh. i Elektron.* **1**, No. 6 (1956).