

Ignition and Surface Temperatures of Double Base Propellants at Low Pressures II. Comparison of Optical and Thermocouple Techniques

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The two most popular temperature measurement techniques for solid-propellant research, infrared and thermocouple, are compared on the basis of experiments involving the simultaneous use of both techniques. It is found that the fine-wire thermocouple measurements are more reliable than the optical measurements, and that temperature measurements at the burning surface are subject to error with both techniques, on account of the gaseous products of the solid decomposition. An analytical solution for the preignition warmup under external radiation is also included, in addition to a numerical technique for computing the infrared emission from a finite depth of propellant under steady burning.

Nomenclature

c_1	= first radiation constant, 3.745×10^{-5} erg-cm ² -sec ⁻¹
c_2	= second radiation constant, 1.4387 cm-°K
c_p	= specific heat at constant pressure, cal/g-°K
$F(x)$	= photon free path distribution
I_λ	= monochromatic radiant emission from a volume
I_0	= externally applied radiant flux, cal/cm ² -sec
I_0'	= $I_0/\rho c_p$
k_s	= thermal conductivity of solid, cal/cm-sec-°K
$r_{\lambda 0}$	= reflectivity at wavelength for which $\epsilon_\lambda = 0$
T	= absolute temperature
T_b	= temperature of black body emitter
T_i	= propellant ignition surface temperature
T_0	= ambient (initial) temperature
T_s	= propellant burning surface temperature
t'	= transmittance of surface boundary
t_λ	= transmittance at wavelength λ (monochromatic)
$t_{\lambda 0}$	= transmittance at wavelength λ for which $\epsilon_\lambda = 0$
v	= linear propellant burning rate
W	= total radiant intensity of a real emission surface
W_λ	= monochromatic emittance of a real body
$W_{b\lambda}$	= monochromatic emittance of a blackbody
x	= linear distance
x_{max}	= depth at which 95% of incident radiation is absorbed
α	= thermal diffusivity $\alpha = k_s/\rho c_p$
α_λ	= monochromatic absorptivity
β	= mean radiation extinction coefficient, cm ⁻¹
β_λ	= monochromatic extinction coefficient
γ_λ	= monochromatic scattering coefficient
ϵ_λ	= monochromatic emissivity of an opaque surface
$\epsilon_{\lambda x}$	= monochromatic emissivity of a film of thickness x
$\epsilon_{\lambda(\Delta x)}$	= monochromatic emissivity of a depth emission element Δx
κ_λ	= monochromatic absorption coefficient
λ	= photon wavelength
λ_p	= photon mean free path
ρ	= mass density, g/cm ³
μ	= micron, 10^{-4} cm

I. Introduction

IN the past two decades considerable effort has been expended to determine the structure and dominant mechanisms of the various reaction zones of solid-propellant

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combustion. Several theoretical models have been advanced¹⁻⁴ in an attempt to describe the experimentally observed dependence of the deflagration rate upon the ambient conditions of temperature and pressure. It has been found that the combustion process is a complex combination of solid and gas phase reactions, with the possibility of a transitional liquid phase.^{2,5} The thermal structure (temperature profile) of the various zones has been taken as the primary experimental evidence of the presence of reactions, in conjunction with chemical analysis studies. There are, however, many problems associated with the determination of the temperature profile to the degree of accuracy necessary for qualitative analysis of the reaction zones, such as the three-dimensional character of deflagration, and the transient nature of the chemical reactions.

A thorough exploitation of the one-dimensional models has, however, led to the development of important experimental techniques, particularly in the areas of temperature instrumentation. The two major techniques are optical (infrared) and thermocouple measurements, although less direct calorimetry methods have also been used with limited success.⁵ Many investigators^{3,6-15} have used either or both of the techniques to measure the burning surface temperatures of various propellant compositions, but little has been done to reconcile the extreme variations in the measured values. Certainly, the limitations of both techniques are easily obtained (i.e., Powling and Smith⁸), but it has not been clarified whether the wide range of measured temperatures is the fault of the instrumentation or due to inherent instabilities in the solid-propellant combustion phenomena.

The basic contribution of the present work is that measurements using both techniques were made simultaneously, to provide a valid experimental basis for comparison. Following an outline of the infrared and thermocouple methods, the advantages and limitations of each will be discussed in terms of both theoretical and experimental considerations.

II. Thermocouple Method

Although the companion paper⁹ gives a thorough discussion of the thermocouple technique, it will be briefly reviewed here. The thermocouple measurements involve two basic experimental configurations, depending upon whether or not the subsurface temperature profile is to be found in addition to the surface temperature.

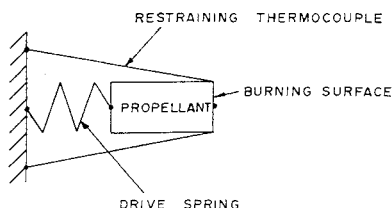


Fig. 1 Stationary burning surface apparatus (after Heller and Gordon³).

A. Embedded Thermocouples

Measurements of the surface temperature and subsurface temperature profile have been made by means of fine thermocouples embedded in the propellant strand. Using 40 μ Pt-Pt (10% Rh) thermocouples, Klein et al.¹¹ measured a temperature rise of 1730°C over a distance of about 600 μ (which includes part of the flame zone) in 0.16 sec. With such a large temperature gradient across the thermocouple junction, the results thus obtained have questionable accuracy. Analysis of the fizz reaction gases above the burning surface indicated components upon which the bare-metal thermocouple would have a catalytic effect.

Strittmatter et al.,¹² using very thin junction (5 μ in the burning direction) Pt-Pt (10% Rh) thermocouples, reported a sharp break in the temperature profile between 300° and 400°C for M-13 propellant burning at 200 psi. High-speed movies of the thermocouple emergence indicated that the break occurs about 40 μ below the observed burning surface, and that the emergence temperature was 535°C. It was pointed out, however, that 11% of the heat input to the junction was lost by conduction through the leads, even for such a thin junction. The lead loss would be much greater for the thermocouples used by Klein et al.¹¹

The thermocouple lead loss and response analysis by Suh and Tsai¹⁶ enabled them to predict more accurate values of temperature for spherical thermojunctions, by taking into account the transient heat transfer between the propellant and the thermocouple for realistic temperature profiles and burning rates. They found that the experimentally obtained profile could be adjusted to a "correct" profile by matching assumed surface temperatures with measured bead temperatures. They found that there is a temperature plateau when the thermocouple emerges from the surface, as did Zenin.¹⁷ The plateau is more apparent when the size of the thermocouple wire is small.

B. Surface Thermocouples

Heller and Gordon³ measured surface temperatures by fine thermocouples held on the stationary burning surface by spring-loading the propellant as shown in Fig. 1. However, simultaneous moving pictures of the surface and flame zone showed the flame striking back near the thermocouple each time a high temperature recording was made. The propellants used were PL-673, P1-725, and PL-748, whose compositions are similar and average 55% nitrocellulose and 43.5% nitroglycerine. Their techniques have been employed in the work presented here, for simultaneous thermocouple and infrared surface temperature measurements. On account of the thermocouple response characteristics, surface thermocouples give a more accurate indication of surface temperature than embedded thermocouples, but they cannot be used to determine the temperature distribution in the propellant.

III. Optical Method

The optical method for measuring burning surface temperatures of solid propellants was first used by Powling and Smith.⁷ It is based on the well-known principles of radiation

heat transfer. The standard of reference for thermal radiation is the black body, which is both a perfect emitter and a perfect absorber of radiant energy. Blackbody radiation is described by Planck's law,

$$W_{b\lambda} = c_1 \lambda^{-5} / [\exp(c_2/\lambda T) - 1] \quad (1)$$

The monochromatic emittance of any real body is related to that of a blackbody at the same temperature by

$$W_\lambda = \epsilon_\lambda W_{b\lambda} \quad (2)$$

Since absolute radiant intensity measurements are difficult to make, a reference blackbody is used and the surface temperature is computed from Eqs. (1) and (2)

$$T_s = c_2 / \{ \lambda \ln [W_{b\lambda} \epsilon_\lambda / \{ \exp(c_2/\lambda T_b) - 1 \} / W_\lambda + 1] \} \quad (3)$$

The apparatus is so arranged that the geometric view factors of the blackbody and the propellant surface with respect to the monochromator and sensor are equal.

The inherent difficulties, in this method are pointed out by Powling and Smith⁸ as follows

1) The gas in the flame zone is emitting at a higher temperature than the surface, and the flame-gas density increases with pressure. This difficulty is partially resolved by so constructing the apparatus that the flame gases are purged away from the surface by a counterflow of inert gas, and also by extrapolating total emission vs time to time zero,¹⁸ since the gas depth increases in a known manner. The proper choice of measuring wavelength for high surface emissivity and low flame emissivity is also an important factor. Powling and Smith⁷ found that flame and gas emission for ammonium perchlorate show strong peaks at selected wavelengths, superimposed on a weak continuum. For double-base propellants, however, it has been found that the radiant emission in the combustion zone is a strong continuum,^{13,19} with sufficient intensity to mask the surface emission at infrared wavelengths.

2) The infrared radiation is emitted from a finite volume of the propellant over a wide range of temperatures. The emissivity is a function of both temperature and wavelength, so surface temperature measurements cannot be made without prior knowledge of the propellant emission characteristics. Under the generally valid assumption that temperature does not alter the strong emissivity peaks significantly, the apparent surface temperature can be measured on the basis of room temperature emissivity measurements. The problem of the emitting layer remains, however, to be analyzed. The steep temperature gradient at high ambient pressures causes the emissivity of the thin radiating surface layer to be rather uncertain, resulting in an anomalous fall in apparent surface temperature at high pressures and burning rates.

The effective emissivity of a thin layer of material at constant temperature is determined from the free path distribution of incident photons. If κ_λ = monochromatic absorption coefficient, γ_λ = monochromatic scattering coefficient, and $\beta_\lambda = \kappa_\lambda + \gamma_\lambda$ = monochromatic extinction coefficient, then

$$F(x) = \exp(-\beta_\lambda x) \quad (4)$$

is the probability of a photon of wavelength λ having a free path exceeding x , and the mean free path would be

$$\lambda_p = 1/\beta_\lambda \quad (5)$$

For most metals, λ_p is of the order of a few microns, so that radiant emission and absorption are essentially surface phenomena. For nonconductors, however, λ_p varies widely with wavelength. The average emissivity of a surface layer of thickness x is found by integrating the emission from each differential element dx over the probability function in Eq.

(4), giving

$$\epsilon_{\lambda x} = \epsilon_{\lambda} [1 - \exp(-\beta_{\lambda} x)] \quad (6)$$

where ϵ_{λ} is the opaque emissivity. Since we are concerned only with the high emission bands for temperature measuring purposes, $\kappa_{\lambda} \gg \gamma_{\lambda}$, so that Eq. (6) becomes

$$\epsilon_{\lambda x} = \epsilon_{\lambda} [1 - \exp(-\kappa_{\lambda} x)] \quad (6a)$$

Powling and Smith⁸ arbitrarily chose the effective depth emissivity to be that of the surface layer of a certain thickness, within which the temperature is within 5% of the surface temperature. They used a high κ_{λ} for measuring wavelength in order to minimize the thickness of the emitting layer. James¹⁰ suggested integrating the surface emission over the entire depth of the propellant for an assumed hyperbolic temperature distribution, in order to obtain a closed-form solution for the entire temperature profile on the basis of a few experimental measurements. A theoretically more valid profile is obtained from the moving-boundary energy equation

$$k_s(d^2T/dx^2) + \rho c_p v(dT/dx) = 0 \quad (7)$$

which gives the temperature distribution

$$T = T_0 + (T_s - T_0) \exp(-\rho v c_p x / k_s) \quad (8)$$

A typical distribution is given in Fig. 2, where $T_s = 600^\circ\text{K}$ and $T_0 = 300^\circ\text{K}$. At a given wavelength, the emissivity of an element Δx is obtained from Eq. (6)

$$\epsilon_{\lambda(\Delta x)} = \epsilon_{\lambda} [1 - \exp(-\beta_{\lambda} \Delta x)] \quad (9)$$

The radiant emission from the element is obtained from Eq. (1), corrected for angular emission (see James¹⁰)

$$\Delta I_{\lambda} = (c_1/\pi \lambda^5) \{ \epsilon_{\lambda(\Delta x)} / [\exp(c_2/\lambda T) - 1] \} \quad (10)$$

The fraction of ΔI_{λ} that is emitted from the surface is given by Eq. (4)

$$\Delta W_{\lambda x} = t' \exp(-\beta_{\lambda} x) \Delta I_{\lambda} \quad (11)$$

Since the emission from the surface passes into a medium of lower index of refraction, for normal incidence we take $t' = 1$. The spectral emission for wavelength λ is then

$$W_{\lambda} = \sum \Delta W_{\lambda x} \quad (12)$$

and the total emission from the surface is

$$W = \sum_{\lambda} W_{\lambda} \Delta \lambda \quad (13)$$

The set of Eqs. (8-13) was programmed for the computer to determine the depth emission W for a given medium band

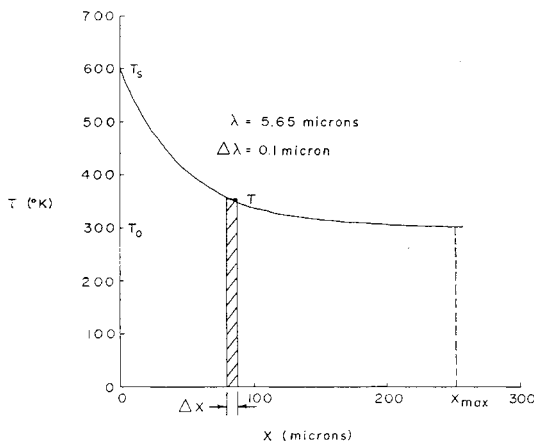


Fig. 2 Typical steady burning temperature profile for depth emission analysis.

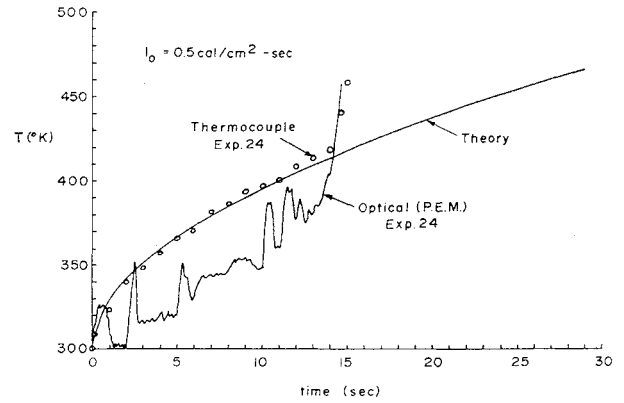


Fig. 3 Preignition surface temperature for M-2 propellant with an external radiant flux.

pass filter. The final values of intensity can then be correlated to those of a calibration blackbody to determine the surface temperature. The limit on the depth of emission x_{\max} was taken as the depth from which only 5% of the emission reaches the surface. Since the absorption is exponential, this corresponds to

$$x_{\max} = 3.0/\beta_{\lambda} \quad (14)$$

For assumed values of T_s and T_0 , W was computed for values of the burning rate, v , varying over the entire range pertinent to low-pressure solid-propellant combustion. Since T_0 , W , and v are known for each experiment, T_s may be determined directly from the computed calibration curves.

IV. Preignition Surface Temperature

As with steady-state burning, the subsurface temperature distribution should be taken into account with the measurement of the ignition temperature by infrared emission. For this analysis, consider a semi-infinite slab at initial temperature T_0 subjected to a step function radiation input I_0 at zero time. Assuming constant propellant properties, the energy equation for a differential element dx is

$$\rho c_p (\partial T / \partial t) = k_s (\partial^2 T / \partial x^2) + I_0 \beta \exp(-\beta x)$$

or

$$(\partial T / \partial t) = \alpha (\partial^2 T / \partial x^2) + I_0' \beta \exp(-\beta x) \quad (15)$$

where $\alpha = k_s / \rho c_p$ and $I_0' = I_0 / \rho c_p$. The boundary conditions are 1) $T(\infty, t) = T_0$, 2) $\partial T(0, t) / \partial x = 0$. Equation (15) was solved, subject to the given boundary conditions, by use of Laplace transformation techniques. The pre-ignition profile was found to be

$$T(x, t) = T_0 + (I_0 / \rho c_p) \{ \exp(-\beta x) [\exp(\alpha \beta^2 t) - 1] / \alpha \beta + 2(t / \pi \alpha)^{1/2} \exp(-x^2 / 4 \alpha t) - x \operatorname{erfc}[x / 2(\alpha t)^{1/2}] / \alpha + \exp(\alpha \beta^2 t) \{ \exp(\beta x) \operatorname{erfc}[x / 2(\alpha t)^{1/2} + \beta(\alpha t)^{1/2}] - \exp(-\beta x) \operatorname{erfc}[x / 2(\alpha t)^{1/2} - \beta(\alpha t)^{1/2}] \} 2 \alpha \beta \} \quad (16)$$

The preignition surface temperature is then

$$T(0, t) = T_0 + I_0 \{ (1 / \alpha \beta) \{ \exp(\alpha \beta^2 t) \operatorname{erfc}[\beta(\alpha t)^{1/2}] - 1 \} + 2(t / \pi \alpha)^{1/2} \} / \rho c_p \quad (17)$$

Figure 3 shows the close agreement between Eq. (17) and the experimental results for M-2 propellant heated to ignition in a partial vacuum (1 psia).

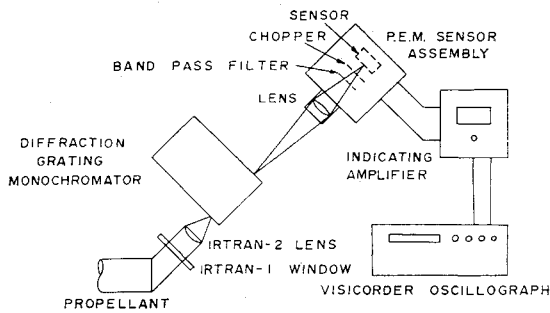


Fig. 4 Infrared burning surface temperature measurement apparatus.

V. Experimental Method

A. Spectrographic Analysis of Propellants

Transmission spectra are determined by passing radiation through thin films or solutions. The films used in this project were cast from acetonic solutions of varying propellant concentrations: the stronger the solution, the thicker the film. The solution was deposited evenly on glass slides with a medicine dropper and allowed to solidify at room temperature by evaporation of the acetone. After solidification, the films were removed from the slides by water displacement and the thickness measured with a micrometer.

The percent of radiation transmitted by films of known thickness in the wavelength range of 2.5 to 16μ was recorded on a Perkin-Elmer IR-257 Grating Infrared Spectrophotometer. The emissivities at selected wavelengths were determined by assuming band emission only. That is, $\epsilon_\lambda = \alpha_\lambda = 0$ outside the bands so that $r_{\lambda 0} = 1 - t_{\lambda 0}$. If specular reflection is not affected by band absorption,

$$\epsilon_{\lambda x} = 1 - t_\lambda - r_{\lambda 0} = t_{\lambda 0} - t_\lambda \quad (18)$$

The monochromatic absorption coefficient was determined from Eq. (6a):

$$\kappa_\lambda = -\ln[1 - \epsilon_{\lambda x}/\epsilon_\lambda]/x \quad (19)$$

B. Surface Temperature Measurements

A schematic of the optical system for surface temperature measurements is shown in Fig. 4. Radiation emitted from the burning surface is passed through an IRTRAN-1† window in the combustion chamber end plate to an IRTRAN-2‡ collimating lens, which focuses it onto the entrance slit of a Jarrell-Ash Quarter Meter Diffraction Grating Monochromator (Model 82-410). The monochromator was equipped with a 98 grooves/mm reflection grating blazed at 7.0μ . The 100μ factory-installed slits were replaced by $\frac{1}{8}$ -in. slits, since the angular dispersion is much less for the 98 grooves/mm grating than for the 1180 grooves/mm standard grating, and the low intensity level of propellant emission requires a larger detector area. With the larger slits, the bandwidth of the radiation at the exit slit is 0.12μ at 6μ wavelength.

The lens system of a Honeywell P.E.M. Cell Pyrometer is focused on the exit slit of the monochromator. The signal is chopped at 1120 sec^{-1} within the sensor assembly. The sensor element is an indium antimonide photoelectromagnetic cell whose spectral response is from 2 to 7μ . The sensor output is amplified and rectified by the Indicating Amplifier assembly and then recorded on a Honeywell Visicorder Oscillograph (Model 1508) using an M200-120 subminiature galvanometer.

A schematic of the combustion chamber is shown in Fig. 5. The propellants are ignited by a radiant heater a short dis-

tance from the ignition surface and burned horizontally. The four other ports in the conical end plate contain 1) window and lens for infrared surface temperature measurement, 2) electrical leads for thermocouples and the shutter system of the igniter, 3) viewing window or high-speed movie camera, and 4) 150-w lamp (variable from 0 to 24 v).

The shutter consists of an aluminum plate moved up and down by a d.c. solenoid. The propellant stand is comprised of an aluminum plate mounted on the conical end plate, on which the brass propellant holder block and thermocouple terminals are mounted. A light spring encased in a hollow Plexiglas cylinder drives the specimen against a 1-mil Alumel-Chromel thermocouple initially put on the propellant surface. The spring tension was adjusted such that the thermocouple bead always remained on the surface when observed under forty power magnification and a small variation in the tension did not change the measured temperature. The output of the thermocouple is recorded simultaneously with the P.E.M. output on the Visicorder, using a M200-350 subminiature galvanometer. The inert gas and vacuum lines enter the chamber through the rear end plate. A wide range of ambient chamber temperatures and pressures is made available by the inert gas control network. Argon was the chamber gas used in these experiments. Initial heating or cooling is accomplished by passing a steady flow of air through the system until the desired initial temperature is reached. The argon is then introduced at a low flow rate until the desired chamber pressure is reached. In order to determine if there was any catalytic effect due to the presence of the thermocouple, platinum and platinum - 10% rhodium thermocouples were also tried. The results were the same.

VI. Experimental Results

The qualitative and quantitative aspects of the spectrographic analysis agree favorably with the work of Powling and Smith.⁷ A typical spectrum for M-2 propellant is shown in Fig. 6. The changes in propellant radiative properties after ignition have been neglected in this work. Experimentally, however, there appears to be little change in the infrared bands used here. The measured emission curves are continuous, and when the ignition source is removed instantaneously while the propellant is burning, the decrease in measured emission corresponds identically with the initial increase when the radiant source is instantaneously cut on. It is therefore concluded that the infrared reflectivity of the surface is not significantly different under burning conditions.

A series of experiments were run at pressures of 1, 2.5, 5, 12.5, and 14 psia, with M-2 propellant. A typical oscillograph record for the spring-mounted specimens is given in Fig. 7. Considerations for reduction of the data are as follows:

A. Surface Reflection

At point A in Fig. 7, there is an instantaneous rise in the P.E.M. trace when the shutter is opened, while there is a

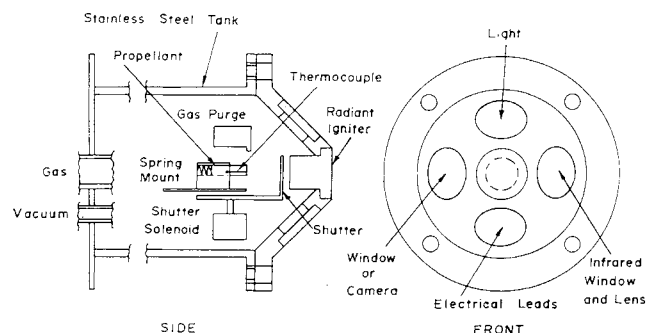


Fig. 5 Low-pressure propellant combustion chamber.

† Kodak trademark for infrared transmitting materials.

gradual increase in the slope of the surface thermocouple trace. It was found that if the shutter is closed either before or shortly after ignition, there is an identical instantaneous decrease in the measured intensity. It is therefore concluded that the sudden change is caused by the reflection of incident radiation from the propellant surface and is essentially constant for a stationary surface. It is then necessary to subtract an amount AB (Fig. 7) from the P.E.M. deflection for an accurate temperature measurement. Calibration of the radiant ignition source indicates that the magnitude of the jump corresponds to a surface reflectivity of about 0.1, which is consistent with the spectrographic analysis. After the initial jump AB , the P.E.M. output rises in a manner similar to that of the surface thermocouple.

B. Propellant Position

The optimum location for the propellant surface was found by moving a small resistance-heated plate back and forth in the mounting block until a maximum P.E.M. output was obtained. It was found that essentially all of the recorded radiation comes from an area slightly smaller than the propellant cross section. Improper positioning of the specimens can be easily identified on the Visicorder record, since there is a marked decrease in the initial reflection (described previously) and the point of ignition is not clearly defined (there is a little change of slope at ignition).

C. Ignition Surface Temperature

The ignition point is marked by sharp increases in the slopes of both the thermocouple and P.E.M. traces and should occur at the same time on both traces (points C and E in Fig. 7). The slight increase in the slope of the thermocouple trace prior to ignition may be accounted for by the exothermic solid phase reaction. The surface thermocouple provides positive identification of the ignition point and is therefore recommended for use in the proper evaluation of the radiant emission (P.E.M.) data.

D. Burning Surface Temperature

On the thermocouple trace, the plateau after ignition (point D in Fig. 7) corresponds to the burning surface temperature for spring-mounted specimens. For the galvanometer instrumentation used here, the resistance of the thermocouple circuit must be measured prior to each experiment. The reference junction is maintained at room temperature, which is also recorded. The thermocouple mv output is determined from the resistance and galvanometer current response, related to a reference junction at 0°C ; then the temperature is found from standard thermocouple tables.

The point marked F in Fig. 7 is taken as the burning surface temperature on the P.E.M. trace, where there is a

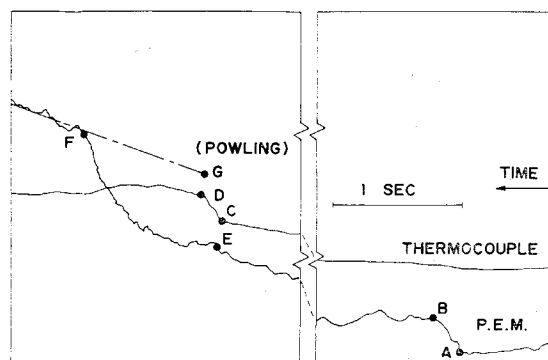


Fig. 7 A typical oscillograph record for ignition of M-2 propellant: experiment 24, spring drive, $5-7\ \mu$ P.E.M. filter.

significant decrease in slope. The time difference between D and F is about 1 sec in most of the spring-mounted experiments. Visual observation shows that at low pressures the ignition is not planar, and the combustion wave takes a few seconds to spread over the surface. Since the thermocouple measurement is essentially a point phenomenon and the optical measurement is averaged over the emitting surface, it is expected that ignition will appear to be instantaneous on the thermocouple trace and gradual on the P.E.M. trace. A thermocouple breakage problem with the spring-mounted specimens prevented surface temperature measurements at pressures above 5 psia.

E. Combustion Products

At low pressures, the exhaust products form an oily residue on the IRTRAN-1 window, so the measured intensities become increasingly unreliable during the course of the experiment. It is therefore necessary to clean the window before each experiment and to extract the data as soon as possible after ignition. A rectangular nozzle was mounted above the propellant in some of the experiments to purge away the gaseous products with a moderate stream of inert gas (argon), but at very low ambient pressures it was found to be not very effective.

Figure 8 shows both the thermocouple and optical results, with only the wide-band $5-7\ \mu$ filter data adjusted for depth emission. The raw data for ignition temperature were adjusted for depth emission by assuming that the pre-ignition temperature profile is closely approximated by that of a propellant burning at a very slow rate ($0.01\ \text{cm/sec}$). The exact solution for the temperature profile, Eq. (16), could be put into the depth emission computer program for more accurate adjustments. The optical ignition temperature T_i

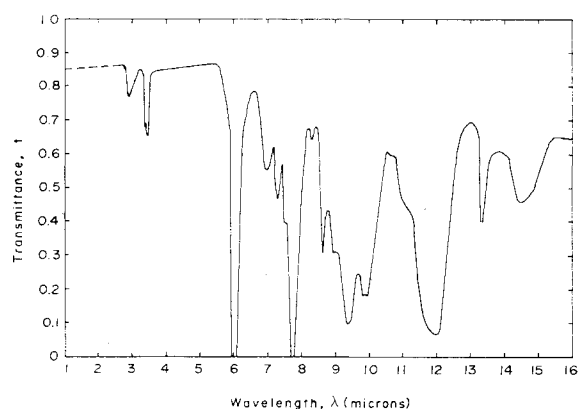


Fig. 6 Spectral transmittance of M-2 propellant, film thickness $10\ \mu$.

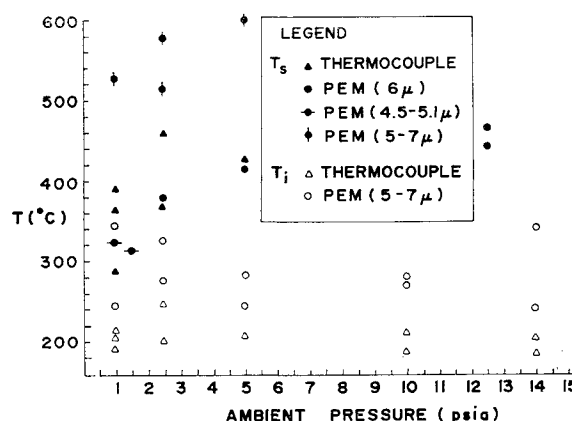


Fig. 8 Ignition and burning surface temperatures of M-2 propellant at partial vacuum pressures.

for M-2 propellant initially at room temperature ranges from 244° to 343°C (average 280°C), and it does not vary significantly for ambient pressures from 1 psia to 14 psia. The thermocouple measurements range from 185° to 245°C (average 200°C) for the same specimens. Probable sources of the discrepancy between the two techniques include:

- 1) inaccuracy of the assumed subsurface temperature profile used in the adjustment of the optical data,
- 2) radiant emission from gases evolved before ignition. Kirby and Suh²⁰ found that there is significant solid decomposition even at temperatures too low for sustained combustion,
- 3) interaction between surface thermocouple and evolved gases. This would account for the wide scatter in the thermocouple measurements.

As shown in Fig. 8, the 5-7 μ filter data, adjusted for depth emission, give the highest indications of the burning surface temperature, T_s , ranging from 527°C at 1 psia to 606°C at 5 psia. The few values obtained with the 4.5-5.1 μ filter and an assumed surface emissivity $\epsilon = 0.9$ are lowest of the several techniques (around 320°C at 1 psia), since that wavelength band is "transparent" (Fig. 6) and therefore the measured emission comes from a significant depth of propellant. Among the optical techniques used, the monochromator (6 μ) data appear to agree most closely with the thermocouple measurements at low pressures, varying from $T_s = 380^\circ\text{C}$ at 2.5 psia to $T_s = 450^\circ\text{C}$ at 12.5 psia. At a given pressure, however, there is a scatter in the thermocouple data of about 100°C, so quantitative comparison with the optical measurements is not feasible on the basis of these experiments. The monochromator (6 micron) measurements are comparable to those of Powling and Smith⁷ for double-base propellants of similar burning rates. Point G (Fig. 7) corresponds to the optical temperature measurement reported in Powling's⁷ work, where the slope of the emission curve is extrapolated to the time of ignition. The point F, however, is more readily identifiable than G in cases where the ignition point is not independently determined (e.g., by thermocouples or fuse wires), and it is unlikely that the emission from the gas varies linearly with time. The high surface temperature measurements are obviously affected by even a very small amount of high-temperature evolved gases. The steady-state thermocouple measurements⁹ indicate that the burning surface temperature is actually very close to the ignition temperature reported here.

VII. Conclusion

In light of the discrepancies between the thermocouple and optical measurements, it is concluded that accurate infrared instrumentation is limited to high-emissivity wavelengths when a subsurface temperature gradient exists. Attempts to predict the ignition temperature by considering an emitting volume, while accurate, require prior knowledge of at least the shape of the temperature profile.

The steady-state burning surface temperatures of deflagrating double-base solid propellants can only be estimated from the radiant emission data immediately after ignition, since the dark zone constituents show significant emission in the infrared measuring wavelengths. When a luminous flame is present (at higher pressures) the high flame zone emission precludes determination of the burning surface temperature, so that only the ignition temperature can then be determined optically.

It is concluded that the optical technique is not as effective as the thermocouple technique for double-base propellants, and that the measurements from embedded thermocouples⁹

are more reliable than surface thermocouples, considering the errors induced by the gases evolved at the surface.

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