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Microwave Doppler Shift Technique for Determining Solid Propellant Transient Regression Rates

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A microwave Doppler shift system, with increased resolution over earlier microwave techniques, was developed for measuring the regression rates of solid propellants during rapid pressure transients (10^4 to 10^5 N/cm^2-sec). The system was used in two different transient combustion experiments: a rapid depressurization bomb and in the high-frequency acoustic pressure environment of a T-burner. In the rapid depressurization tests the measured apparent regression rates generally fell near or below the steady-state rate at the corresponding pressure and exhibited oscillations in tests near the critical depressurization rates for extinguishment. Unreasonably high oscillatory regression rates were obtained in the T-burner experiments. The results of a set of parameteric calculations indicated that flame ionization effects could be of sufficient magnitude to account for these anomalies. A direct comparison of the analytical predictions and experimental results yielded the conclusion that flame ionization effects probably produced some errors in the absolute values, but not the general characteristics, of the rapid depressurization regression rate measurements.

Nomenclature

A = ratio of microwave test signal to reference signal amplitudes
b = waveguide path length, see Fig. 2
c = waveguide path length, see Fig. 2
d = width of transition zone
e = base of natural logarithm
k_p = microwave propagation constant in propellant
k_w = microwave propagation constant in empty rectangular waveguide
l = propellant sample length
l_0 = total propellant length burned in a test
P = pressure
r = apparent propellant regression rate
r' = amplitude of regression rate oscillations
t = time
Y = mole fraction of ionizable species (Na)
$\Delta\omega$ = beat frequency of superimposed microwave signals
λ_p = microwave wavelength in test propellant
Φ = phase difference between microwave test and reference signals
Φ_0 = total microwave phase shift in a test
Φ_s = burning surface phase shift component of Φ
ω_i = angular frequency of incident microwave signal
ω_r = angular frequency of microwave signal reflected from regressing propellant surface

Superscript

$\cdot$ = rate of change with time

Subscript

0 = steady-state value prior to pressure transient ($t < 0$)

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I. Introduction

AN area of solid propellant rocket technology that has received a considerable amount of study is the burning of solid propellants under conditions of rapidly changing, i.e., transient, pressure. Two examples of such conditions are termination of rocket thrust by abruptly dropping the rocket chamber pressure (rapid depressurization extinguishment) and high-frequency acoustic combustion instability, which can involve pressure transients greater than 10^5 N/cm^2-sec. The characteristic time of such pressure transients can approach, and be less than, the characteristic response time of the combustion process. Under such conditions propellant burning rates would

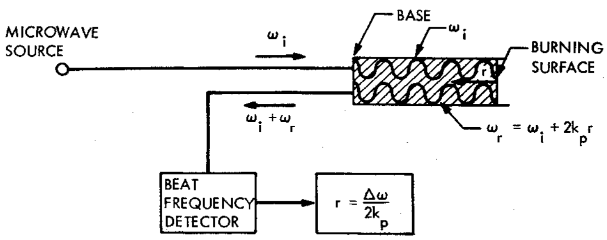

Fig. 1 Doppler shift principle.

be expected to deviate from steady-state predicted values. Theories devised to describe the above phenomena generally contain some type of expression, explicit or otherwise, for the nonsteady regression rate.[1-9] In the past direct evaluation of such nonsteady-state combustion modeling has been hampered by the lack of comprehensive experimental data with which to compare theoretical results. The objective of this program was to develop a technique for providing such information.

The system finally arrived at yields an apparent regression rate by measuring the phase angle difference between an incident microwave signal propagating up a burning propellant test sample and the portion of the wave reflected from the regressing propellant-flame zone interface. Regression rate data were obtained under two highly transient pressure conditions: 1) during rapid depressurization in a combustion bomb, and 2) in the high-frequency oscillatory pressure environment of a T-burner. Data were taken for several propellant formulations containing ammonium-perchlorate (AP) oxidizer with either polyetherpolyurethane (PU), hydroxy-terminated polybutadiene (HTPB), or carboxyl-terminated polybutadiene (CTPB) binder systems.

II. Summary of Earlier Results

There have been a variety of ways, besides actual measurement of the regression rates, in which attempts have been made to experimentally observe the transient response of the combustion process to rapid perturbations in pressure. For single perturbations (pressurization or depressurization) these have included dynamic pressure,[7,10-12] thermocouple,[13] optical,[14-16] and spectral[16,17] measurements of various types.

The response of a burning surface to oscillatory or harmonic pressure waves is commonly characterized by the response function, the dimensionless ratio of the mass flux perturbation normal to the propellant surface to the pressure perturbation. Considerable experimental investigation has been devoted to determining its magnitude and phase and how it varies with pressure, frequency, and propellant composition.[5,18] The experimental response function is generally calculated from the measured rate of growth and decay of pressure oscillations in special burners of simple geometry (L*-, T-burner). Gaseous temperature and composition measurements have also been made using optical[19] and spectral[20] means, respectively.

Attempting to summarize these previous studies, the transient response of the solid propellant combustion process has been shown to be highly complex, featuring lags in response, oscillatory or iregular burning, and, for sufficiently high depressurization gradients, partial or complete extinguishment. As will be shown in Sec. VII, the transient regression rate data obtained in the present study generally agree with these observations.

III. Experimental Technique

To obtain regression rate data under transient pressure conditions a technique with extremely accurate propellant-length resolution is required. For example, consider a propellant burning at a rate of 0.75 cm/sec. If a depressurization occurs over a time interval of 15msec, an average propellant displacement of 110 μm can be expected. To obtain reasonable definition of the regression rate curve a minimum of 10 points would be desirable. This requires resolution of 10 μm or better. Obviously, mechanical, thermocouple, or optical scanning of the flame location are not satisfactory, especially considering that the oxidizer crystals may be of the order of 100 μm. The only previous technique claiming the required resolution is a variable capacitance system,[21] which will be discussed in subsection VII-A-4.

For the past several years a program was carried out to develop and test a transient burning rate measurement system by substantially improving the resolution of earlier microwave techniques (Refs. 22–24, for example). Because of their low resolution, these earlier burning rate measurement techniques were suitable for use only in quasi-steady situations. A microwave system was first used for transient regression rate measurements by S. V. Shelton at the Jet Propulsion Lab.[25] following the introduction of a high resolution, fast response microwave network analyzer. The work presented here was done using Shelton's basic apparatus.

The principle of previous microwave techniques is illustrated in Fig. 1. A continuous microwave beam of frequency ω_i is transmitted to the base of a burning propellant sample. Reflections are generated at both the base of the sample and the burning surface. The base reflection remains at the incident frequency, but the frequency of the burning surface reflection is Doppler shifted by an amount $2k_p r$. This result is obtained by applying two successive Galilean transformations to a plane wave. The superposition of these two reflected signals produces a beat frequency, $\Delta\omega = \omega_r - \omega_i$, which is measured by the detector (see Fig. 1), and from which the regression rate is calculated using the Doppler shift expression

$$\Delta\omega = 2k_p r \tag{1}$$

This method is incapable of resolving rapid regression rate changes during pressure transients due to the long time required to determine the beat frequency; ($T_{\text{beat}} = 2\pi/\Delta\omega \approx 1$ sec).

The present microwave technique achieves greater resolution by monitoring the phase angle difference between the incident and reflected signals. The phase angle principle is illustrated in Fig. 2. The reference and test channels in Fig. 2, which monitor the incident and reflected signals, respectively, are the two input channels of a microwave network analyzer, which continuously measures the phase difference between the two signals. This phase difference can be separated into two parts: 1) path length phase difference (Doppler shift), and 2) burning surface phase shift. The difference in path length between the two measurement points produces a phase difference proportional to the path length. The constant of proportionality is known as the propagation or phase constant and depends on the geometry of the waveguide and the dielectric constant of the medium filling the waveguide. Here, in Fig. 2, we have two separate phase constants: k_w for the empty rectangular waveguide leading to the propellant sample and k_p for the propellant sample tube. From Fig. 2, this part of the phase difference is given by

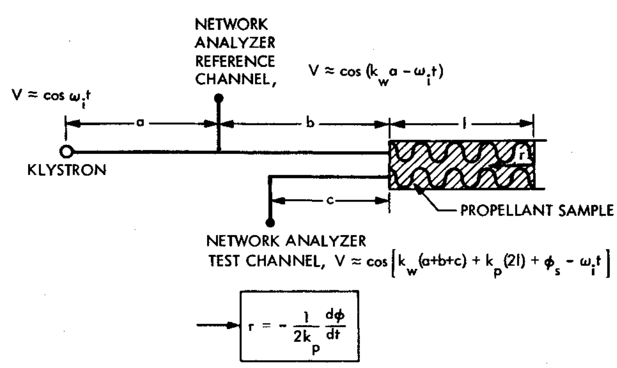

Fig. 2 Phase shift principle.

$$\Phi_{\text{path length}} = k_w(b+c)+k_p(2l) \quad (2)$$

The second component of the total phase difference, the burning surface phase shift, Φ_s, is caused by the jump in wave impedance at the burning surface. Its magnitude is dependent on conditions at the propellant-flame interface. It will be assumed to be constant for now, and be discussed in greater detail in Subsection VII-C. The total phase difference is thus given by

$$\Phi_{\text{total}} = k_w(b+c)+k_p(2l)+\Phi_s \quad (3)$$

Differentiating with respect to time and noting that $dl/dt = -r$, we finally obtain

$$d\Phi/dt = -2k_p r \quad (4)$$

The phase constant, k_p, is calculated from the same phase-vs-time record used in the regression rate calculation. The total propellant length burned and the total phase shift for an entire test are substituted into the integrated form of Eq. (4) to yield:

$$k_p = -\Phi_0/2l_0 \quad (5)$$

Combining Eqs. (4) and (5), we obtain the final expression for the regression rate as a function of $d\Phi/dt$

$$r = (l_0/\Phi_0)(d\Phi/dt) \quad (6)$$

The wavelength of the microwave signal in the test propellant can also be calculated from the phase-vs-time record

$$\lambda_p = \frac{l_0}{\Phi_0/720°} \quad (7)$$

Substituting Eq. (7) into Eq. (6) yields another form of the regression rate equation

$$r = (\lambda_p/720°)(d\Phi/dt) \quad (8)$$

Inserting the measured value for λ_p, it can be shown from Eq. (5) that for a spatial resolution of 10 μm, a phase angle resolution of approximately 0.5° is required.

In actual practice the reflected signal into the network analyzer contains a small component oscillating at the source frequency, ω_i, due to reflections from impedance mismatches within the microwave system, which superimposes an oscillation of frequency $2k_p r$ on the phase angle signal. This has little effect on the transient measurements, since the time scale of the transient events is usually much smaller than the period of the superposed oscillation, but for burning rate measurements during gradual pressure changes this oscillation must be taken into account in reducing the data. A more detailed description of this effect is given in Ref. 25.

IV. Apparatus and Procedure

A block diagram of the microwave system is presented in Fig. 3. The radio frequency source is a reflex klystron operating near 10 GHz and stabilized by an oscillator synchronizer to $1/10^8$ Hz. The power level was 0.3 mw. The basic microwave transmission system is standard rectangular X-band waveguide with coaxial cable leads to the instrumentation and a short section of circular waveguide near the combustion bomb. Immediately following the Klystron is a 20-db directional coupler that diverts 1% of the Klystron output to the oscillator synchronizer for frequency stabilization and to a thermistor for power measurement. A ferrite isolator, which allows signal propagation in the forward direction only, is inserted to minimize the effect of reflected signals on the rf source. The second directional coupler diverts another 1% of the power to the reference channel of the microwave network analyzer for comparison with the signal reflected from the propellant sample. The remaining signal then passes through the E-H tuner, a reversed 10-db directional coupler, and the slide tuner to the propellant burning surface. The directional couplers are designed to couple only radiation propagating in a specified direction into the external circuit, thus minimizing the problem of mixing incident and reflected signals in the channels of the network analyzer. Signal mixing, or cross-talk, is further reduced by the E-H tuner, which is placed between the couplers to the network analyzer.

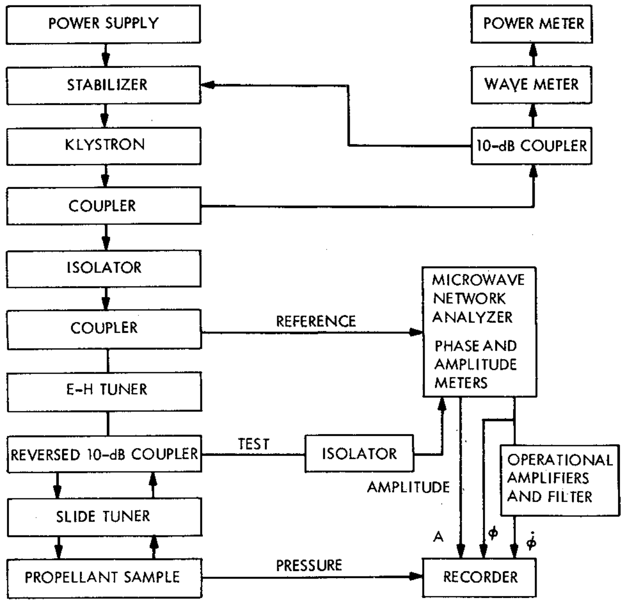

Fig. 3 Microwave system block diagram.

The slide tuner located before the propellant sample is used to tune out the reflection from the base of the propellant sample. The signal reflected from the burning surface propagates back through the waveguide system to the reversed 10-db directional coupler, which diverts 10% of the reflected signal to the test channel of the network analyzer, which, in turn, produces d.c. voltages proportional to the phase and amplitude differences of the reference and test channel signals. The phase and amplitude relationships of the reflected and reference waves were initially determined by means of three Hewlett-Packard instruments: the Model 8411A Frequency Converter, the Model 8410A Network Analyzer, and the Model 8413A Phase-Gain Indicator. The frequency converter and network analyzer, together, comprise a two-channel microwave receiver, and the phase-gain indicator detects the phase and amplitude relationships of one channel with respect to the other.

Eventually a Dranetz Engineering Labs., Inc., Model 305 High Accuracy Phase Meter was incorporated to measure the phase difference between the reference and test signal outputs of the wave analyzer. Its d.c.-signal output is remarkably free of high-frequency noise, containing only the 278-KHz carrier frequency of the wave analyzer. It is capable of resolving a phase difference of $\pm 0.25°$ up to a frequency of 500 KHz, allowing a propellant surface spatial resolution of 5.4 μm.

With this clean phase signal, differentiation and amplification, employing two Type 3A8 Tektronix Operational Amplifiers, permitted the propellant transient regression rate to be measured directly. From Eq. (8) the amplifiers were calibrated prior to each test using triangular wave signals from a Hewlett-Packard Model 3310 Function Generator.

The main difficulty in this differentiation operation is the generation of large-amplitude signals from low-amplitude noise impressed upon the phase signal at some point(s) in the circuit. The spurious noise on the differentiated signal (60 Hz, 300 Hz, and higher harmonics) was reduced to an acceptable level without destroying valid lower frequency data or the necessary frequency response by using a 60-Hz narrow-band notch filter and selective low-pass filtering with a sharp cut-off filter (Dynamics Model No. 6371).

The microwave path through the propellant is shown in Fig. 4. The propellant samples are encased in 1.59-cm ($\frac{5}{8}$-in.) i.d., 5.1-cm (2-in.) or 10.2-cm (4-in.) long steel tubes, threaded at each end, which serve as waveguides for the microwave. A large part of the fixed reflection in the microwave system originates at the propellant lower interface, since at this point the micro-

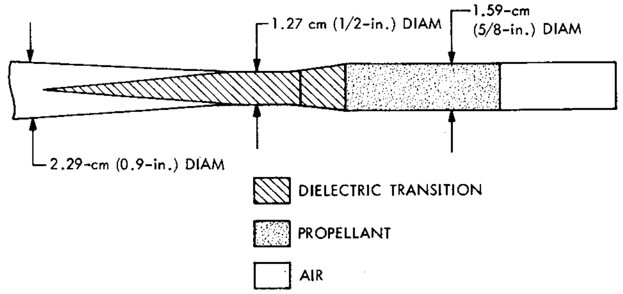

Fig. 4 Microwave electrical path.

wave signal must make a transition from the air-filled rectangular waveguide to the propellant sample, which is effectively a dielectric-filled circular waveguide. To minimize the discontinuity at this transition a long cone of Melmac plastic with dielectric properties similar to those of the propellant is inserted before the propellant sample. In addition to reducing the reflection from the air-propellant interface, the cone serves as a pressure sealing "window" for the test base-plate.

The inside diameter of the propellant tube was sized to propagate with low losses only the microwave dominant mode when filled with propellant, and to be blow cutoff for all frequency modes when empty.

Solid propellant regression rate measurements were conducted under two transient conditions: during rapid depressurization in a combustion bomb and while exposed to acoustic oscillations in a T-burner. The combustion bomb and its on-command venting system, T-burner, pressure measurement instrumentation, and data recording system were all conventional and are described in Ref. 26.

Except for an adapter for mounting one end of the T-burner on the microwave base plate, all T-burner components were developed in a research program conducted earlier at JPL.[27] The lower disk of acoustic driver propellant contained a 2.54-cm (1-in.) hole to allow the test propellant tube to pass through. To obtain reasonable definition of the T-burner oscillatory regression rate with a microwave system spatial resolution of 5 μm, a calculation similar to that presented in Sec. III gives an upper limit frequency of about 150 Hz. In these tests a T-burner length of 51 cm (20 in.) was used, giving a fundamental frequency of approximately 800 Hz. This higher than desirable frequency was dictated by the necessity to be in the region of maximum acoustic response for the A-13 driver propellant. The amplitude of pressure oscillations for this propellant were found to drop off sharply with decreasing frequency.[27]

Test procedures, which were basically the same for the two types of experiments, are given in detail in Ref. 26. After the propellant tube was screwed into the base plate a tuning operation was performed to minimize the magnitude of the fixed reflections in the system (typically 70 db or more below the reference signal amplitude after tuning).

Ignition of the propellant sample and, in the T-burner tests, the two disks of driver propellant was accomplished by electrically heating a piece of nichrome wire which ignited a pyrotechnic paste (supplied by the Naval Weapons Center at China Lake, Calif.) spread on the propellant surface.

V. Propellants

The four propellants used in this study are listed in Table 1, along with general details of their composition. The 540A propellant has a near stoichiometric composition and is very clean burning. The other three propellants are underoxidized and burn quite smokily.

A majority of the tests were conducted using the first two propellants. The 540A formulation has been used extensively at JPL in combustion instability studies.[27,28] The CTPB propellant

Table 1 Test propellant compositions

Propellant	Binder/ oxidizer	Binder/oxidizer concentration, %	Oxidizer mass median diam, μm
540A	PU[a]/AP[b]	20/80	30%—17 70%—170
HTPB	HTPB[c]/AP	17/83	30%—17 70%—170
CTPB	CTPB[d]/AP	25/75	33%—17 67%—90
CTPB (modified)	CTPB/AP	25/73 (2% Al)	33%—17 67%—90

[a] Polyether-polyurethane.
[b] Ammonium perchlorate.
[c] Hydroxy-terminated polybutadiene.
[d] Carboxyl-terminated polybutadiene.

and a slightly modified version of it are based on a formulation used by investigators at the Univ. of Waterloo in another effort to measure the transient regression rates of propellants undergoing rapid depressurization.[21] The regression rates of the JPL-mixed propellants were somewhat higher, probably due to different oxidizer size distributions. These latter two propellants were used primarily in the T-burner experiments.

A propellant, designated A-13 (supplied by the Naval Weapons Center at China Lake, California), which has been found to be very unstable in a number of prior T-burner studies (Ref. 27 as an example), was used as the acoustic driver propellant in the T-burner experiments. It is an ammonium perchlorate oxidizer propellant with polybutylacrylonitrile acrylic acid as the binder.

Dielectric constant measurements (supplied by S. V. Shelton, Georgia Institute of Technology, Atlanta, Ga.) obtained for 540A propellant yielded a mean dielectric constant of 4.9 and a loss tangent of 0.02. The dielectric constant of the Melmac transition cone was 5.

VI. Verification Tests

Several experiments were conducted to verify the spatial and time resolution of the regression rate measurement, the effect of propellant surface roughness and compressibility on the measurements, and the accuracy of the system for quasi-steady-state regression rate measurements. In one test, the details of which are given in Ref. 26, the propellant sample was replaced with a column of Dow-Corning Oil with a dielectric constant similar to that of propellant, and the phase shift was measured while fine droplets of oil were dropped on the oil column surface. It was concluded from these tests that the experimental apparatus had a surface resolution of at least 50 μm (limited by minimum droplet size) and time response in the ms range.

In a second test, 400-μm crystals of ammonium perchlorate were dropped onto the surface of a partially filled propellant sample tube at varying positions on the surface. The tests verified that for the typical roughness scale of regressing pro-

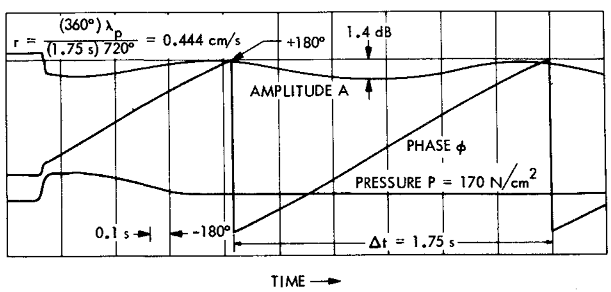

Fig. 5 Segment of oscillograph test record.

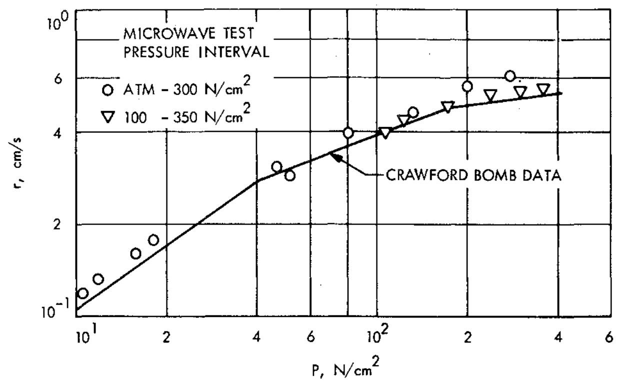

Fig. 6 Regression rate data comparison for 540A propellant.

pellants the propellant surface still appears planer to the microwave signal.

A number of steady and quasi-steady regression rate measurements were obtained to check the accuracy of the instrumentation and theory. In the ready-state runs, the combustion bomb was pressurized to a desired level; the propellant sample was ignited and allowed to burn to completion at a relatively steady pressure.

Figure 5 is a representation of a segment of the oscillograph record from one such test for 540A propellant. Depicted are the pressure, phase angle, and the amplitude ratio of the reflected signal (the operational amplifier was not used in these early tests). Because the pressure was constant after the initial ignition transient, the linearity of Φ and the magnitude of the oscillations of A provide a measure of how well the fixed reflections were tuned out. If only the burning surface reflection had been present, the phase channel would have a constant slope, and the amplitude would have gradually increased as a result of a decreasing propellant path length.

The amplitude channel exhibits an abrupt jump of approximately 2 db immediately following ignition of the propellant sample. An amplitude increase of this magnitude or less after ignition was quite common, although usually not as abrupt. Static tests showed that mounting an empty 5.1-cm (2-in.) long tube on a propellant sample tube produced a 5-db or larger increase in the amplitude of the reflected signal. It was concluded from these tests that the propellant surface itself is not a good reflector. Instead, as the propellant ignites and regresses down the tube, the hollow tube behind the surface cuts off transmission, and a larger portion of the incident radiation is reflected.

Although less than two phase cycles are shown in Fig. 5, there was a total of 13.2 for the entire 10.2 cm (4 in.) of propellant. The microwave wavelength in the propellant, obtained from Eq. (7), was 1.55 cm.

Measuring the derivative of Φ with respect to time for one cycle from Fig. 5, the calculated regression rate from Eq. (8) was 0.444 cm/sec, which compares with a rate of this pressure of 0.470 cm/sec from Crawford Bomb burning rate data. There was a slight progressivity of the regression rate over the complete run, probably due to heat conduction to the unlined metal walls of the propellant tube.

To measure the regression rate of a sample over a wide pressure range, the bomb was sealed after ignition, allowing the sample to pressurize the bomb as it burned. This pressurization can be considered quasi-steady since pressurization rates were typically a few hundred N/cm^2-sec. No attempt was made to control the strand temperature. Test results for 540A propellant are compared with Crawford Bomb data for the same propellant formulation in Fig. 6. Agreement during the initial portion of each test is reasonably good, but a progressivity with time in the microwave data is again apparent.

Compressibility effects of the propellant were investigated by subjecting a nonburning propellant sample to pressure transients equal to those imposed on the burning propellant samples. In these rapid depressurization tests, over-all phase shifts of approximately 1° to 2° occurred, indicating propellant length increases of 20 to 50 μm. Such changes are in the same region with predictions based on the propellant bulk modulus. They cannot be considered insignificant. The net result is that the experimentally determined transient regression rates are the result of both a negative burning component and a positive or negative compressibility component (decreasing or increasing pressure), the magnitude of the latter depending on the sample propellant length and physical properties and the test pressure and pressure gradient. Since the compressibility effect is real, and accurately adjusting the transient regression rate data to obtain the burning rate component would be a highly involved, time-dependent process, no corrections were made to the data. It should be interpreted or utilized accordingly.

VII. Transient Regression Rate Measurements

A. Rapid Depressurization Tests

1. 540A propellant

Figure 7 shows the test results for four tests at initial pressures in the 230 to 270 N/cm^2 range. The tests are in the order of ascending rate of depressurization. Shown are the bomb transient pressure, propellant steady-state regression rate at the corresponding pressure, and measured regression rate, each normalized by the initial value at the time of onset of depressurization.

The measured regression rate generally fell below the steady-state value. As shown for the lower depressurization rates, there were a few milliseconds lag in the response of the measured regression rate to the depressurization, followed by an abrupt drop to 0.6 to 0.8 of its initial value. This initial lag diminished and eventually disappeared with increasing rate of depressurization. The propellant in the Fig. 7a test did not extinguish, but slowly recovered to the atmospheric pressure burning rate approximately 1/2 s after the onset of depressurization. In the tests shown in Figs. 7b–d, the propellants all extinguished, with the regression rates smoothly going to zero rather than suddenly terminating. With the largest venting orifice tested, the regression rate abruptly dropped to zero, undershooting it before leveling off to zero. Calibration checks showed no such instrumentation undershoot to an abrupt change in Φ. A possible explanation for this apparent negative regression rate will be discussed in Subsection VII-C.

Beginning with Fig. 7b, the measured regression rate exhibited rather irregular oscillations that were not evident in the pressure signal (however the response time of the chamber was too great to readily discern any pressure variations caused by the regression rate oscillations). The amplitude of the oscillations increased with increasing rate of depressurization, becoming pulse-like in Fig. 7c, and then diminished (Fig. 7d) and eventually disappeared as the rate of depressurization increased, and combustion extinction became more positive. The oscillation frequencies were roughly below 100 Hz, and appeared to have a general trend of decreasing with decreasing rate of depressurization.

2. HTPB and CTPB propellants

Test results for the HTPB and CTPB propellants are shown in Fig. 8. The results for the two polybutadiene (PB) binder system propellants were quite similar and differed significantly from the polyether-polyurethane (PU) binder 540A results. The initial rates of depressurization required to terminate combustion were greater than twice that found for 540A. Also, the regression rate behavior of the HTPB and CTPB propellants generally seemed more "sluggish." The lags in the initial response of the regression rate to the depressurization were about double that of 540A and persisted up to the highest depressurization rates tested. Where the burning was not quenched, the regression rate would oscillate once, drop off almot to zero, and slowly recover and continue at a low rate.

3. Measurement errors

Two possible sources of error in the regression rate data were 1) the drawing of a mean curve through the r channel noise, and 2) correcting the Φ and r signals for fixed reflections in the microwave system. The maximum uncertainty in regression rate due to averaging the noise was estimated at 0.01 cm/sec, a possible error of a few percent. As stated earlier, corrections for fixed reflections were only necessary for the very gradual depressurization experiments (Fig. 7a for example). In general, the corrections did not exceed 3% to 4%.

Not enough data under closely controlled test conditions (P_0, $\dot{P}_0$, etc.) was obtained to make any definite claims concerning the reproducibility of the results. Because of the short duration of the tests, there was not sufficient time to accurately control by manual means the bomb pressure after initial pressurization and ignition of the propellant strand. The initial rate of depressurization was also difficult to reproduce. This was probably related to how cleanly the burst diaphragm ruptured.

4. Comparison with existing data

As mentioned earlier, the only other transient regression rate data currently available is that of Yin and Hermance.[21] The method of measurement consisted of using a solid propellant strand as the dielectric material of a capacitor forming a part of a L-C tuned circuit in an electronic oscillator. The variation in resonant frequency of the oscillator with change in propellant length was converted into a voltage and differentiated electronically to obtain a voltage directly proportional to the propellant regression rate. The effect of flame plasma on capacitance was reportedly subtracted out electronically.

Even attempting to take into account the differences in the two experimental systems (Yin and Hermance used a rarefaction tube), several fundamental discrepancies between the respective data still seem to exist. Yin and Hermance reported their transient regression rates to be greater than the steady-state rate at the corresponding pressure until extinction occurred. In the present study, this was generally not the case, and occurred only early in the depressurization at the lowest rates tested. In tests using 1) a propellant with the same formulation as that used by Yin and Hermance (CTPB),[21] and 2) the same propellant (HTPB),[29] the JPL results did not exhibit the low-frequency oscillations of the Yin-Hermance transient rate data. Instead, the measured rates exhibited a characteristic S-shape (Fig. 8).

The regression rate data seem to generally agree with the previous findings of Steinz and Selzer[16] and others: 1) at depressurization a brief delay followed by rapid and complete extinguishment of the flame for sufficiently large depressurization rates, 2) for lower rates a recovery and persistence of the flame until near the end of the pressure transient, where the flame then either begins to recover or extinguishes, and 3) irregular burning of the recovered flame near the critical depressurization rates for extinguishment. The lower than predicted regression rates of

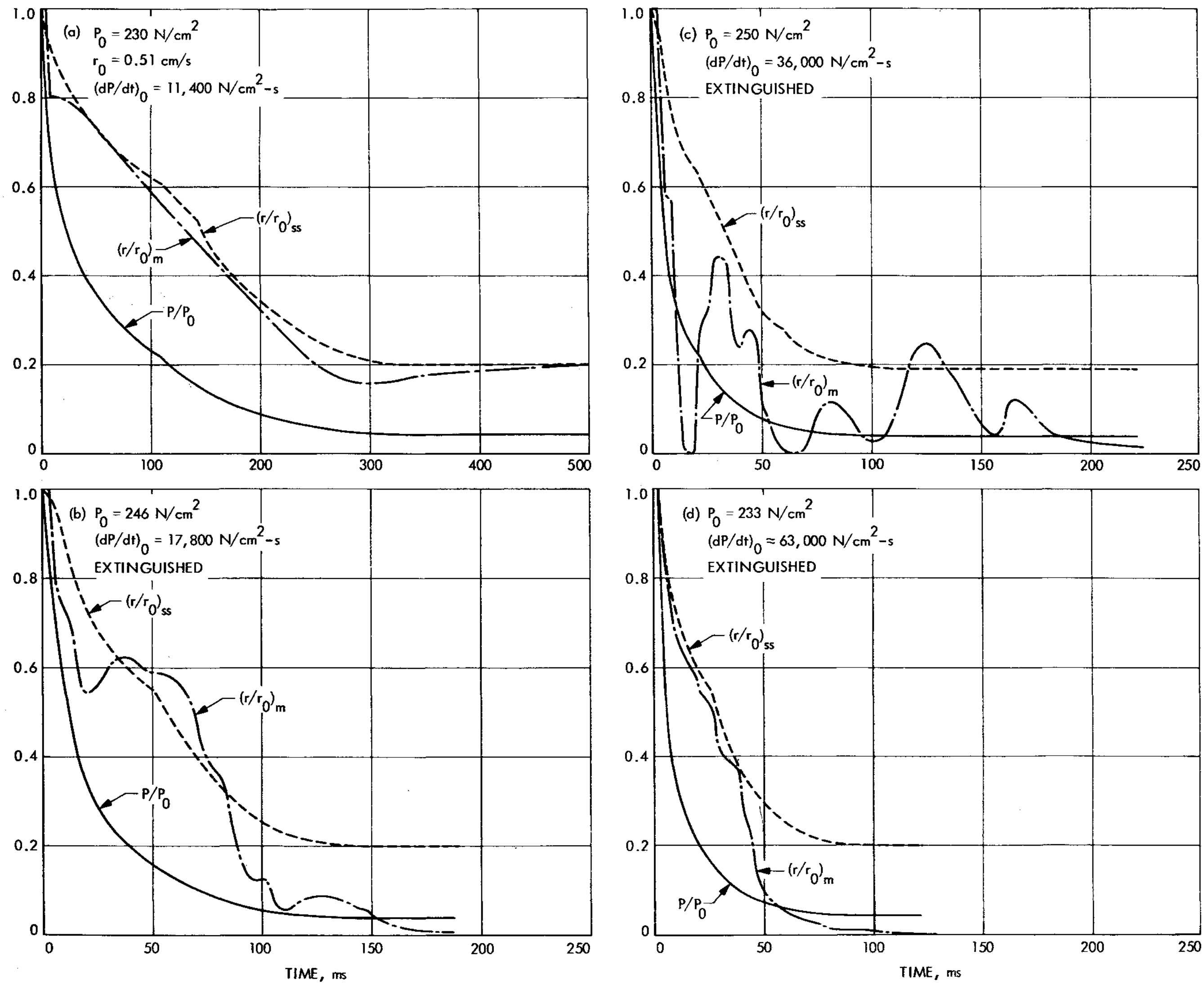

Fig. 7 Rapid depressurization experimental data for 540A propellant: initial pressure of 230 to 270 N/cm^2.

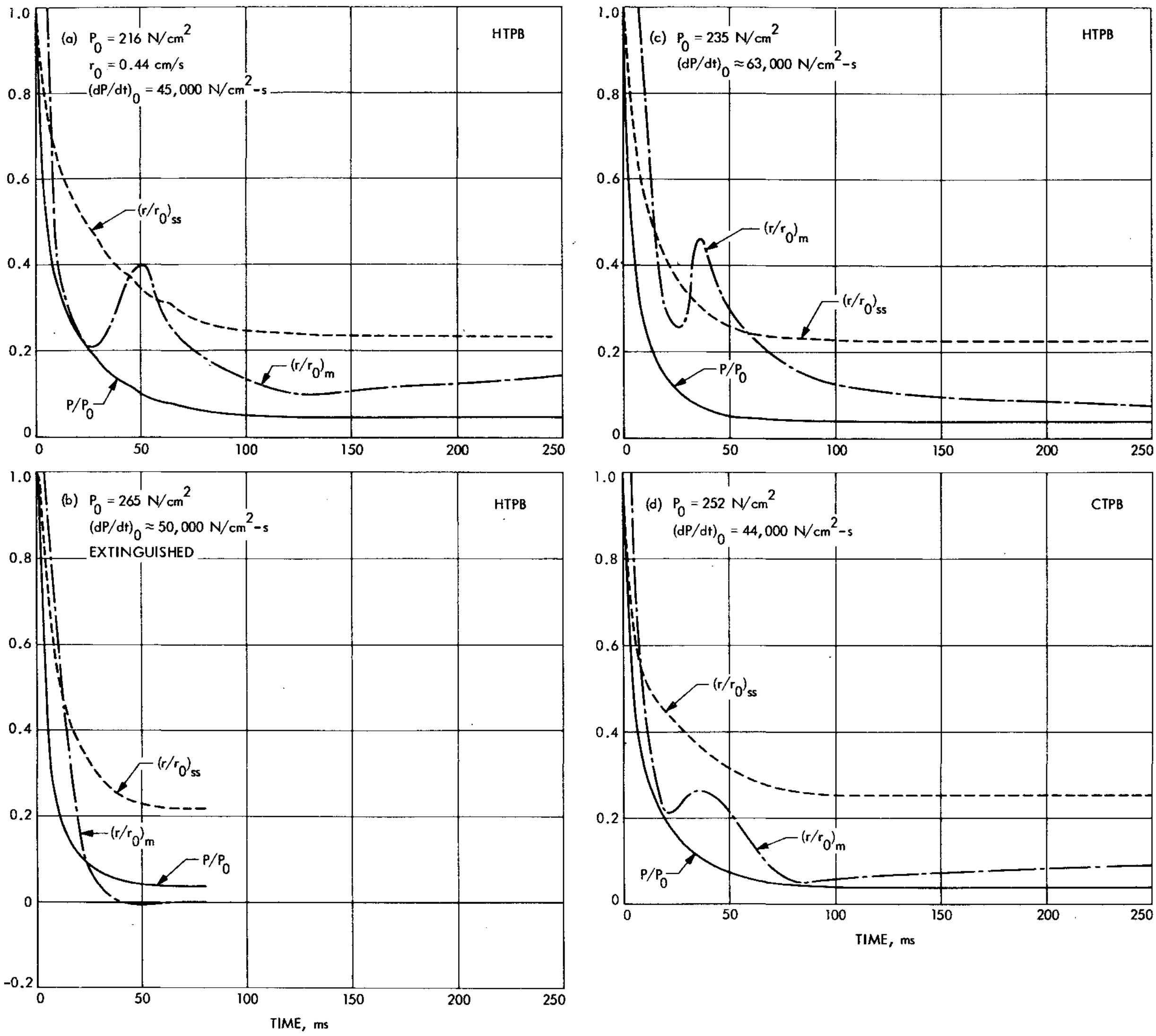

Fig. 8 Rapid depressurization experimental data for HTPB and CTPB propellants.

the PB binder propellants following the pressure transient could be due to only partial recovery of this secondary flame, i.e., the flame had not yet spread over the entire burning surface.

B. T-Burner Tests

A total of 20 tests were performed with the four test propellants. The surge tank pretest pressure in about half of the tests was approximately 180 N/cm^2. This gave a mean T-burner pressure during the test of 220 to 230 N/cm^2 and gave the strongest limiting pressure oscillations (45 N/cm^2 peak-to-peak and greater). For over-all amplitudes greater than 70 N/cm^2 the basically sinusoidal waveform began to exhibit distortions due to higher harmonic frequencies.

For the first half of the tests, difficulties were encountered with wave distortions of the phase and amplitude signals.[26] These were eventually eliminated by the incorporation of a 5.1-cm (2-in.) extension tube to the propellant stand. The tube served as a microwave attenuator, preventing any portion of the signal from being transmitted into the T-burner, reflected, and transmitted back into the microwave propellant strand.

The resulting experimental regression rate signals generally exhibited high-frequency oscillations during a portion of the burn time of the T-burner (Fig. 9). The oscillations would appear and then disappear. Their amplitudes were unreasonably high, one to five or more times the measured mean values. As can be seen, the regression rate signal oscillations lead the pressure by roughly 90°. Correcting for the phase shift of the differential amplifier, the phase lead of r over P was 60°.

C. Plasma Effects Analysis

Two findings make the experimental results somewhat suspect: 1) at the maximum depressurization rates tested the r signal dropped to negative values (Fig. 8b), and 2) in T-burner tests, the amplitudes of the r signal oscillations generally equaled or

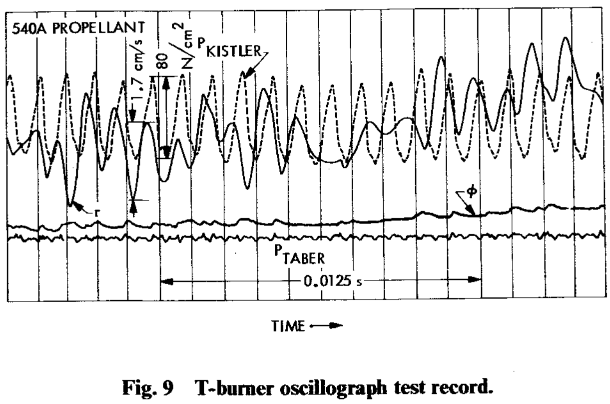

Fig. 9 T-burner oscillograph test record.

exceeded the mean regression rates. Such high response would be more indicative of gaseous rather than solid phase fluctuations.

The primary assumption made in deriving Eq. (6) was that the phase change at the burning propellant surface was essentially constant. Thus, it became of no importance when the total phase difference was differentiated.

As pointed out by Plett and Summerfield[30] in a recent analysis of the effect of flame zone ionization level on the microwave measurement of solid propellant transient burning rates, this assumption is not necessarily valid for transient combustion. Due to transient plasma concentrations, the phase change at the surface can vary significantly with changes in pressure. During periods of rapid pressure transients, these phase changes over short time intervals contribute substantially to the apparent regression rate.

Plett and Summerfield calculated an apparent propellant regression rate, as measured by the microwave phase shift technique, including both the Doppler shift (the actual burning rate) *and* a propellant/plasma interface phase shift caused by transients in the flame zone ionization level. To obtain a possible indication of the magnitude of this effect in the present experiments, parametric calculations were carried out for several simulated test conditions using a modified version of the analytical procedure of Plett and Summerfield.

Details of the analytical procedure are given in Ref. 26. A microwave frequency of 10 GHz and propellant waveguide diameter of 1.27 cm were assumed. The microwave constants of the experimental microwave regression rate apparatus were somewhat different, but the calculated results for the two sets of constants would be very similar. Normalizing to initial conditions at a pressure of 200 N/cm^2 and substituting dielectric and ballistic parameters evaluated to correspond approximately to that for 540A propellant, the following expression was obtained for the apparent regression rate:

$$r/r_0 = (P/P_0)^{0.415} + \frac{\dot{\Phi}_s}{202°/s} \tag{9}$$

where the first term on the right-hand side is the assumed actual regression rate and the second term is the spurious contribution resulting from the variation with pressure of the flame zone plasma density. For any assumed transient pressure profile the surface phase shift rate was evaluated as $\Delta\Phi_s/\Delta t$ for discrete time changes corresponding to discrete pressure changes.

Plasma effects calculations were carried out using both exponential pressure decay and sinusoidal pressure inputs, simulating rapid depressurization and T-burner test conditions respectively. Only the latter will be discussed here.

The following sinusoidal pressure input was used:

$$P(\mathrm{N/cm^2}) = 152 + 15.2 \sin [2\pi t(ms)/1.2] \tag{10}$$

This corresponds to a frequency of 830 Hz, and a peak-to-peak amplitude of 31 N/cm^2, conditions similar to those at which fluctuations in the measured regression rate were observed in two of the latter T-burner tests with propellant extension tubes.

The mole fraction of ionizable species, Y, (simulated by sodium in these calculations) was varied by factors of 10 from 10^{-8} to 10^{-5}. The flame standoff distance was assumed to vary with pressure according to the expression

$$d = d_0(P_0/P) \tag{11}$$

A d_0 mean value of 10^{-3} was assumed.

The results of the calculations, shown in Fig. 10, were quite sensitive to Y. For $Y = 10^{-8}$ the apparent oscillatory regression rate was almost identical to the assumed actual value, giving an r/r_0 amplitude of 1.04. For increasing Y, r/r_0 amplitudes of 1.16, 3.25, and 21.3 were obtained for Y values of 10^{-7}, 10^{-6}, and 10^{-5}, respectively, (r'/r_0 values of 0.16, 2.25, and 20.3). Also, interestingly, the calculations predict an increasing apparent burning rate phase lead with increasing Y, equaling approximately 75° for $Y = 10^{-7}$.

Comparing the results with experimental r'/r_0 data, Y values somewhere between 10^{-6} and 10^{-7} are needed for agreement.

As was found by Plett and Summerfield, the analysis predicts that the use of microwaves to measure transient regression rates only gives accurate results when the propellant has a very low concentration of easily ionizable metals.

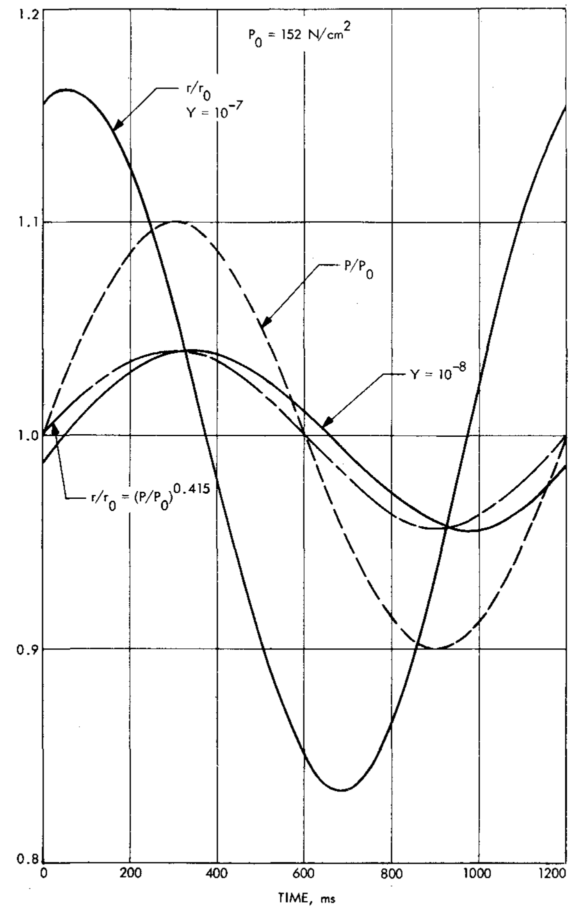

Fig. 10 Results of apparent transient burning rate calculations: sinusoidal pressure oscillation.

No attempts were made to measure the free electron concentration in the flame zone. A typical chemical analysis report for AP lots used in the test propellants showed alkali metal to be present in the form of $NaBrO_3$ and $NaClO_4$, 0.008% by weight each. Nonalkali metals accounted for 0.002% by weight. Spectrophotometer analysis of the prepolymers used in the test propellants yielded alkali and nonalkali metal contents of 10^{-4} to 10^{-3}% by weight.

Due to the electron affinity of the halogen species present, equilibrium thermochemical calculations predict free electron mole fractions of less than 10^{-8}. However, as recently pointed out for solid propellant rocket exhaust plume after-burning, electrical properties calculations based on the assumption that local thermochemical equilibrium is established can be greatly in error.[31]

VIII. Conclusions

A direct comparison of the analytical predictions and experimental results yielded the conclusion that the unrealistic regression rate measurements obtained in the T-burner and in the highest depressurization rate experiments can be accounted for by flame ionization effects on the microwave measurements. Considering the rapid depressurization experiments as a whole, it is concluded that for increasingly greater pressure gradients, the absolute values, but not the over-all nature of the microwave regression measurements, are probably somewhat in error because of flame ionization effects (erring on the high side). Since an accurate knowledge of the free electron concentrations in the propellant flame zones was not available, it is difficult to make a more quantitative statement as to the accuracy of the test measurements.

The present microwave system has demonstrated high spatial and time resolution, and, if propellants free of easily ionizable impurities can be prepared, should be applicable for combustion bomb transient regression rate measurements.

Finally, the propellant compressibility effects tests illustrated a possible additional application for the high spatial resolution of the test system, as a means of accurately determining the bulk modulus of solid propellants.

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