

SURFACE EFFECTS OF FLAME SPREADING
OVER IGNITING COMPOSITE
SOLID PROPELLANT CONSTITUENTS

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ABSTRACT

An experimental investigation of the mechanism by which a flame spreads over the surface of igniting composite solid propellant constituents has been conducted in the Combustion Laboratory of the Mechanical Engineering Department. The mechanism underlying this phenomenon is unknown, although it is of interest to designers of solid propellant rocket motor ignition systems.

The velocity of flame spreading over the surface of two thermoplastics, polystyrene (PS), and polymethylmethacrylate (PMM) in quiescent, oxidizing-gas environments, and over the surface of ammonium perchlorate (AP) in a quiescent, fuel-gas environment, was measured as a function of pressure level, chemical nature and reactivity of the surrounding environment, and specimen surface conditions.

The effect of surface geometry on flame spreading velocity was studied by employing test specimens of loosely packed beads, hydraulically pressed beads, chemically bonded beads, and smooth-surfaced solids. Test specimens were prepared and mounted in a relatively

large, vacuum tight, chamber. Following ignition by means of an electrically heated wire, the velocity of flame spreading was measured cinematographically.

Flame spreading velocities were found to vary directly with pressure level, and for the smooth-surfaced solid specimens tested, the experimental results agree qualitatively with a simplified, gas-phase theory of flame spreading that has been developed in this laboratory. When surface geometry factors are introduced, however, there is a marked increase in flame spreading velocity and a departure from the predictions of this theory.

Visual observation of the flame spreading phenomenon over the surface of loosely packed PS beads reveals a "jumping" forward of some elements of the flame, producing ignition at sites ahead of the principal flame front.

From these results, it is postulated that variations in surface geometry probably results in an intensification of the local heat transfer rate, and a net increase in the overall rate at which heat is transferred forward.

A more complex formulation of the gas-phase

flame spreading mechanism will be necessary before it becomes possible to predict flame spreading velocities over rough surfaces, since no simple mathematical model can adequately treat this process. In particular, the complex geometries studied in this investigation led to such massive complications of the energy equation that it was precluded from analytical solution within the scope of the present work.

The findings of increased flame spreading velocity dependence on pressure level as a function of surface geometry may be of practical significance when applied to the design of actual rocket motor ignition systems. Recommendations for future research in this area have been proposed in the hope that a more complete understanding of the mechanism of flame spreading may be obtained.

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SECTION I

INTRODUCTION

During the past decade there has been considerable interest exhibited in solid propellant rocket motor ignition systems. Despite increased investigation into this area, motor ignition systems are still developed according to certain empirical, though not always reliable, guidelines which have been established over the years. Attempts at deriving a rational basis for design have been prevented by a lack of knowledge of the precise mechanism by which propellant ignition takes place, and of the mechanism by which the combustion flame spreads from the ignited to the unignited portion of the surface of the propellant charge.

Solid propellant motor ignition can be considered the transient condition which results in deflagration of the entire propellant surface and development of the operating chamber pressure. The overall motor ignition process can be divided into three principal phases:

The first phase consists of a process by which the igniter supplies energy to the propellant surface and ignition of a portion of the surface is achieved.

In the second phase, heating of the unignited portion of the propellant surface continues, as the flame front spreads to the unignited area. During the third phase, the motor chamber continues to fill with propellant combustion products until the final equilibrium chamber pressure is reached.

The first phase has received considerable attention during the last few years and it is generally believed that it can be described on the basis of either of two postulated models. The gas phase theory of solid propellant ignition (Reference 1) postulates that propellant vaporization, produced by surface heating, leads to exothermic chemical reaction in the gas phase which results in a temperature run-away at an ignition site in the gas phase. The hypergolic theory of ignition (Reference 2), however, is based upon heat release from exothermic heterogeneous reaction between an oxidizing fluid and solid fuel components; when an "autoignition temperature" is reached, stable combustion proceeds without additional external heat addition.

On the basis of current information, it is impossible to determine which of these two theories

is more valid. There is considerable evidence (Reference 3), however, which refutes the much older assumption that composite solid propellant ignition is completely controlled by processes occurring in the solid phase.

During the third phase, following flame spreading, the motor chamber fills with combustion products until the equilibrium pressure is reached. A simple mass balance between the rate at which gas is being generated in the motor and the rate at which it is being expelled very accurately describes this phase of the motor ignition process.

The second phase of motor ignition, the flame spreading phenomenon, represents the least understood and perhaps the most important segment of the overall motor ignition process. At present, igniter designs are governed by what little experimental data has been obtained from actual rocket motor tests. Attempts have been made by some to apply numerical techniques (Reference 4); i.e., the use of high speed electronic computers for generating motor pressure histories during ignition. These methods evolve from solutions of the conservation equations with certain terms

inserted that are quite arbitrary. Such results, however, are of only academic concern, for they reveal little or no understanding of the actual physical processes occurring.

Recently, experimental investigations into this area have resulted in several theories of flame spreading over an igniting propellant surface in dynamic flow environments (References 5,6). With the realization that the ignition process itself is extensively complex, however, a more fundamental experimental approach to the problem was undertaken in this laboratory. Preliminary to an overall investigation of this phenomenon, including the effects of a dynamic flow environment, investigation of the individual influences of several parameters governing flame spreading was undertaken.

A study of the effects of pressure level and chemical reactivity of the surrounding atmosphere (Reference 7) conducted in this laboratory resulted in a proposed theory of flame spreading over an igniting solid propellant, based upon a one-dimensional, gas phase mechanism of flame spreading (see Appendix). In the limited range of experimental parameter variation

employed, the theory was qualitatively supported by the results of critical experiments conducted with double base (nitrocellulose-nitroglycerine) propellants (Reference 7).

In a program designed to investigate further the parameters influencing flame spreading over the surface of igniting composite propellants, an experimental study was undertaken by the author in the Combustion Laboratory of the Mechanical Engineering Department.

A series of flame spreading experiments were conducted employing several composite propellant constituents in differing gaseous environments. It was hoped that by obtaining an understanding of the flame spreading phenomenon of the individual components, a basis for a meaningful attack on the composite system could be generated. Flame spreading over the surface of igniting thermoplastic fuels in an oxidizing environment, and conversely, flame spreading over the surface of a solid oxidizer component in a fuel environment was studied. Also investigated were the flame spreading characteristics of mixtures of varying proportions of fuel and oxidizer components, closely approximating actual composite propellants.

The validity of a one-dimension model for flame spreading was tested by varying the surface conditions of the test samples as an important parameter. Studies over a wide range of surface geometry were made by varying the packing density and the particle size of the propellant constituents tested. Thus, by investigating the influence of these fundamental parameters on the flame spreading phenomenon, it was hoped that a keener insight into this important phase of rocket motor ignition could be obtained.

SECTION II

DESCRIPTION OF APPARATUS AND TEST PROCEDURES

The velocity of flame spreading over the surface of two thermoplastics, polystyrene (PS) and polymethylmethacrylate (PMM) in quiescent, oxidizing-gas environments, and over the surface of ammonium perchlorate (AP) in quiescent, fuel-gas environments, was measured at atmospheric and a series of subatmospheric pressures.

A large, steel, vacuum-tight vessel ($8\frac{1}{2}$ " ID x 18") equipped with an observation window (4" x 6") was employed as a test chamber, so that the flame spreading phenomenon could be observed and recorded cinematographically. The test specimens were ignited by means of an electrically heated wire; the energy being supplied through electrical lead-ins by an autotransformer. Connected to the chamber was a mercury filled manometer and a Model KC-8 Kinney vacuum pump. A large surge tank was also attached to the test chamber in order to minimize pressure fluctuations during the test. A diagram of the system is shown in Figure 1.

In conducting a test, the specimen with a small 1" reference marking fastened to the side was mounted

in the test chamber, which was then sealed, evacuated, and filled with the selected test gas. Evacuation and charging was repeated to insure that the sample was in intimate contact with the test gas. The pressure in the chamber was then brought to the desired level and the specimen was ignited.

Generally, measurement of the flame spreading velocity was accomplished by the use of a cinematographic technique. However, in cases where the flame spreading velocity was reasonably slow (approx. 0.1 in./sec), visual observation was made and spreading times were measured by means of a manually operated stopwatch.

A Bell and Howell, 16 mm 70-DL movie camera, loaded with Kodak Tri-X 16 mm motion picture film was used to record the flame spreading process. The film was analyzed using a Vanguard, model M-16, motion analyzer, permitting the flame propagation distance during a fixed time interval to be obtained. In order to allow time for the initial ignition transient to decay, and for the steady flame spreading rate to be established, only the velocity over the second half of the specimen was measured.

In order to study the effect of surface conditions on flame spreading velocity, specimens of PS, PMM, and AP were prepared with a number of different surface characteristics. Solid specimens of the thermoplastics were prepared by cutting samples ($1\frac{1}{2}$ " x $\frac{1}{2}$ ") from $\frac{1}{4}$ " thick sheets of PS and PMM. The two sides, end faces, and $\frac{1}{16}$ " width strip on each side of the top surface were inhibited with an inorganic cement comprised of water glass and either powdered asbestos or powdered porcelain, so that the flame was constrained to spread only along the length of the top surface, and maintain a flame front that was normal to the direction of spread. A calibrated distance reference was established by fastening a small 1" marking to the side of each specimen. An electrically heated ignition wire was firmly fastened at one end of the top surface to insure uniform and simultaneous ignition.

Surface geometry effects were studied by measuring flame spreading velocities over the surface of loosely packed beads of PS, PMM, and AP, as well as mixtures of these composite propellant constituents. Aluminum stock was cut ($1\frac{1}{2}$ " long x $\frac{1}{2}$ " wide) and formed into a small container ($\frac{3}{8}$ " depth) by milling.

The specimen, in particle form, was poured into this container and lightly pressed to form a level surface. One inch markings were attached to the container and an ignition wire inserted into the sample at one end.

In order to obtain data for varying conditions of surface geometry, a hydraulic press with a specially designed hardened steel mold was used to fabricate 1 cm x 8 cm strands of the test material from loose particles. By subjecting the loosely poured beads within the mold to hydraulic pressures up to 16,000 psi for 10 minutes (in order to relieve internal stresses), a solid strand was obtained. Under magnification, however, discontinuities in the surface were revealed. Although approximately 90% of the surface appeared to be solid, there still existed large voids; i.e., crater-like indentations along the surface of the order of magnitude of the particle diameter. By varying the particle size and the hydraulic pressure, varying conditions of surface geometry were obtained. These samples were then inhibited and prepared for testing in the same manner as the solids.

Flame spreading data was obtained for solid PS

and PMM, for beads and pressed strands of PS (350-420 μ particle size), and for crystals and pressed strands of AP (297-500 μ particle size).

SECTION III

EXPERIMENTAL RESULTS

In a program designed to reveal fundamental knowledge of the mechanism of flame spreading over the surface of solid propellants, preliminary experiments were conducted with typical composite solid propellant components: polystyrene (PS), polymethylmethacrylate (PMM), and ammonium perchlorate (AP). Flame spreading velocity was measured as a function of pressure level, chemical nature and reactivity of the surrounding environment, as well as solid specimen surface characteristics.

The flame spreading velocities for PS and for PMM were obtained in 100% oxygen test gas at a series of pressures ranging between 10 and 30 in. Hg. At each test condition a number of runs were made and each data point reported herein represents acceptable runs--those which exhibited both a steady flame velocity and a uniform flame front.

The data for PS samples in 100% oxygen (Fig. 4) exhibited an interesting characteristic. A plot of flame spreading velocity (V) as a function of chamber pressure (P) level exhibits a functional dependence of

the form: $(V-V_R) = (P-P_R)^n$ where "n" is a constant and V_R and P_R are convenient reference values in the neighborhood of the lower limit of sustained flame spreading. For solid PS specimens, a pressure exponent less than 1 (Fig. 5) was exhibited. This result agreed with previous findings from the study of double base propellants (Reference 7). However, for all samples with rough surfaces; i.e., bonded, pressed, and loosely packed beads, the pressure exponent is greater than 1 (Fig. 5).

For PMM samples, the same general trend is exhibited; as surface conditions are varied, the pressure exponent changes from a number less than 1, to a number greater than 1. In all cases, the PMM flame spreading velocities are less than corresponding PS rates.

These findings indicate that surface characteristics have an important effect on the flame spreading phenomenon. In order to examine this effect further, another series of experiments was conducted using AP in 100% methane test gas; i.e., an oxidant material in a gas-fuel atmosphere. Thus, by interchanging the physical phases of the fuel and oxidizer components,

and vastly changing the chemical nature of the system it was hoped that the essential nature of the influence of surface condition on flame spreading velocity could be isolated.

The results of these tests were remarkably similar to those described above-- they exhibited pressure exponents greater than 1 for non-smooth surfaces, i.e., loose AP crystals, and exponents approaching 1 as the limiting case of a solid was approached with pressed strands of AP crystals.

Also investigated was the characteristics of two component systems which closely approximate actual composite propellants; i.e., loosely packed PS and AP mixtures of varying proportions. When tested in an oxygen atmosphere, the AP retarded the flame spreading of the pure PS in an amount proportional to the AP/PS mixture ratio. In a methane atmosphere, for mixture ratios ranging from one to three, no flame spreading could be sustained. Experiments dealing with the deflagration process of this system have shown that AP/PS mixture ratios must be greater than those studied in order to obtain stable, steady state deflagration (Reference 8). Thus, it appears that

the limiting conditions for flame spreading might be related to the limiting conditions for steady deflagration.

Variations in particle size of the test specimen was found to be an influential factor in flame spreading. Experimental results from PS studies indicate that flame spreading velocities vary inversely with particle diameter in the loosely packed sample. When smaller particles are pressed, however, they more closely resemble a uniform solid structure than do larger particles, and experiment finds that these flame spreading velocities are correspondingly slower.

The use of a cinematographic technique for recording the flame spreading phenomenon proved to be a valuable tool for observing the flame structure. A comparison of the structure of flames spreading over PMM and PS surfaces in oxygen (Fig. 2) showed a well-defined leading edge immediately followed by a large trailing flame plume for the PMM sample, whereas the PS flame was much closer to the surface and exhibited a secondary flame plume which follows approximately $\frac{1}{2}$ " behind the primary flame front.

The most important physical observation is the

apparent "jumping" of the flame front forward from particle to particle in samples composed of loosely packed beads. This phenomenon is readily observable for pure PS beads (Fig. 3) and is also very evident for mixtures of PS and AP in 100% oxygen. In the latter case, the spreading flame seems to "jump" around, searching for PS beads. The AP crystals begin to ignite only after the flame front has passed them. This is evidenced by the appearance of a secondary flame, which is much brighter, and issues many "streamers" into the gas phase, a characteristic of full-scale AP composite propellant deflagration.

These previously unsuspected results shed new light on the mechanism of flame spreading, providing evidence for the need of a more complex model in order to describe adequately the phenomenon of flame spreading over the surface of igniting composite solid propellants.

SECTION IV

DISCUSSION OF RESULTS

A theory of flame spreading over the surface of igniting solid propellants, which is intimately related to the gas phase theory of propellant ignition, has been developed in this laboratory (Reference 7).

In its simplest form, this gas phase theory of flame spreading is based upon a continuous ignition process of the propellant surface exposed to the advancing flame. As the flame approaches a given surface of the propellant, its effects become influential and there is a heating-up and vaporization of the surface layer. As diffusion of these vapors away from the surface takes place, they undergo rapid exothermic chemical reaction with the environment. A temperature runaway results, which leads to ignition in the gas phase at the instant the flame passes that location of the surface. Inherent within this theory are several major assumptions: (1) The distance ahead of the flame that is affected by the presence of the approaching flame (thermal layer thickness) is

assumed constant; (2) Ignition takes place in the gas phase at a constant distance above the surface; (3) The diffusing vapor concentration at the ignition site is proportional to an exponential variation with time; (4) To a first approximation, gas-phase heat transfer at the reaction site is neglected; e.g., the heat generation rate per unit mass, Q_{chem} , is the only source of heat generation.

For flame spreading over the surface of double base solid propellants, this analysis, based on the above assumptions, agrees qualitatively with experimental results (Reference 7); i.e., by predicting a flame spreading pressure exponent less than 1. In fact, as a result of the present investigation of flame spreading over the surface of igniting composite solid propellant constituents, it has been found that for solid thermoplastic specimens (PS, PMM) in an oxygen environment this analysis is supported by experiment. Thus, it appears that the simplified gas-phase theory of flame spreading agrees with experimental findings as long as the test specimen is a smooth-surfaced solid; i.e., when the specimen surface is one-dimensional in the direction of flame spreading.

When the surface conditions are changed, however, and the flame spreading velocity is measured as a function of the varying surface geometries for composite solid propellant components, the experimental results do not agree with the theoretical predictions of this simplified theory.

Pressure exponents greater than 1 for all experimental models (PS, PMM in oxygen and AP in methane) with varying surface geometries indicates that in such cases, the one-dimensional model may be an oversimplification and that a more complex mechanism must be proposed. Observing that a flame will spread faster across rough surfaces than across smooth-surfaced solid specimens, it is postulated that surface geometry probably results in an intensification of the local heat transfer rate, or, in the large, an increase in the overall rate at which heat is transferred forward.

Experimental evidence in support of this postulated increase of the local heat transfer rate arises from observing the flame spreading phenomenon by photographic techniques (Fig. 3). When PS beads were pressed into strands, and flame spreading data recorded,

it was noticed that the flame front moves discontinuously over the sample; i.e., the flame appears to "jump" along the surface. The photographic record of this phenomenon shows the flame front "jumping" forward and igniting particles well ahead of the principal flame front, producing a flame discontinuity along the sample. The flame then appears to propagate forward and also backward toward the still unignited region, eventually reuniting into a continuous flame front (Fig. 3). By observing the "jumping" of the flame front it is postulated that there is an intensification of the heat transferred in the forward direction by one of two mechanisms:

- (1) Thermal radiation traversing the surface discontinuities, thereby increasing the flame spreading velocity; i.e., the flame "jumps" across the voids in the surface before it has an opportunity to conduct downward into them;
- (2) An extension of the "edge effect" observed when the top edge of a solid propellant is not inhibited (Reference 9); i.e., the flame conducts along the sharp

edges of the discontinuities at a speed greater than over a plane surface, thereby increasing the overall flame spreading velocity.

The increased importance of radiation heat transfer effects in flame spreading over non-smooth surfaces has been postulated from observing the photographic record of this phenomenon (Fig. 3). Environmental factors also favoring the intensification of thermal energy radiation are the increased surface area and geometrical configurations present when smaller particle sizes are employed, as well as the increase in flame emissivity as a function of pressure level (Reference 6).

Supporting evidence for the latter hypothesis may be found in the literature wherein it is noted that when burning solid propellant strands contain structural imperfections, oftentimes the flame seems to "wormhole" down these structural cracks. In an attempt to verify this postulate, several samples of solid PMM were indented with a $1/16$ " deep groove along the length of its flame spreading surface. It was observed that the igniting flame propagated

faster along the grooved edge than across a smooth-surfaced specimen of the same material, and in turn, seemed to induce higher velocities of the flame front spreading over the smooth portion of the surface.

Acknowledgement that surface geometry probably results in an intensification of the local heat transfer rate will now require the formulation of a two-dimensional model for flame spreading since a simple one-dimensional model cannot adequately treat this process. For smooth-surfaced solids, the local heat transfer rate is a monotonically decreasing function of position within the thermal layer thickness (the distance ahead of the flame which is significantly affected by its presence). For rough surfaces, however, it is not logical to expect such a simplified variation; indeed, visual observation of the flame spreading process reveals ignition ahead of the flame front. This is an indication that such sites have been exposed to an intensification of thermal energy, probably due to local geometric factors, and that the flame spreading phenomenon requires a two-dimensional mathematical formulation for an adequate description.

By inspection of the analysis for smooth-surfaced specimens (see Appendix) it is possible to identify the expression that would be effected by surface geometry characteristics. The rate at which the diffusing vapor concentration, C_f , builds up at any given distance above the specimen surface is a function of the surface vaporization rate. This, in turn, depends upon the surface heating intensity, which as stated above, is a strong function of surface geometry. Therefore, the complex surface geometries studied in this investigation lead to complications of the energy equation describing the phenomenon that precluded it from analytical solution within the scope of the present work.

Further investigation must be undertaken to determine the exact effects of geometry upon the surface heat-up and vaporization process which leads to the gas-phase reaction.

SECTION V

SUMMARY AND CONCLUSIONS

An investigation of the flame spreading phenomenon over the surface of igniting composite solid propellant constituents has been conducted on a fundamental level. The velocity of flame spreading over the surface of two thermoplastics, polystyrene (PS) and polymethylmethacrylate (PMM) in quiescent, oxidizing-gas environments, and over the surface of ammonium perchlorate (AP) in a quiescent, fuel-gas environment, was measured as a function of pressure level, chemical nature and reactivity of the surrounding environment, and specimen surface characteristics.

The experimental results of this investigation are:

- (1) For smooth-surfaced solid specimens, the flame spreading pressure exponent is less than 1, in agreement with general results obtained for other solid surfaces.
- (2) When surface geometry factors are introduced by means of bonded, pressed, and loosely packed bead surfaces, there is an increase in pressure exponent to a number greater than 1.

- (3) For a given surface condition, flame spreading velocity varies inversely with particle size of the test samples.
- (4) When mixtures of PS and AP are tested in oxygen, sustained flame spreading occurs only in the range of mixture ratios where steady deflagration of these substances has been recorded, and flame spreading velocity varies inversely with the AP/PS mixture weight ratio.
- (5) Visual observation of the flame spreading phenomenon reveals a "jumping" flame front over the surface of loosely packed PS beads and ignition at sites ahead of the flame front.

Based upon these experimental results, several conclusions may be drawn:

- (1) For smooth-surfaced solid specimens, the one-dimensional gas-phase theory of flame spreading (Reference 7), which predicts a simple functional dependence of flame spreading velocity on pressure level, agrees with experimental findings.
- (2) Pressure exponents greater than 1 for all experimental models with varying surface geometries indicates that a more complex formulation of

the gas-phase flame spreading mechanism will be necessary before it becomes possible to predict flame spreading velocities over rough surfaces.

- (3) It is postulated that surface geometry probably results in an intensification of the local heat transfer rate, and an increase in the overall rate at which heat is transferred forward, probably due to local geometric factors.
- (4) In order to account for these geometric factors, a two-dimensional mathematical model must be formulated and a re-evaluation of the assumptions regarding thermal layer thickness and ignition site location must be undertaken.

The increase in flame spreading velocity as a function of surface geometry may be of great practical significance when applied to rocket motor ignition systems. The flame spreading phenomenon is an intermediary stage in the overall motor ignition process and high flame spreading velocities are desired in order to more rapidly attain the final equilibrium chamber pressure. If the effects of surface geometry can be sustained at higher pressure levels, in the

region of actual motor igniter operation, designers of practical ignition systems will have a deeper insight into this phenomenon, and an important guideline for design of these systems.

SECTION VI

RECOMMENDATIONS FOR FUTURE RESEARCH

As reported herein, an experimental investigation of the gas-phase theory of flame spreading on a fundamental level was conducted, and a two-dimensional mechanism of flame spreading proposed. An exact, quantitative analysis of this mechanism requires the solution to a sophisticated mathematical formulation. At present, the nonlinearity of these equations, coupled with the complex geometry and lack of knowledge of the all important boundary condition governing the response of propellant vaporization to surface heating, prove to be a formidable problem. Hence, extensive research must be undertaken in order to gain a complete understanding of this two-dimensional phenomenon.

A logical extension of the present investigation would be to study the effects of surface geometry over a wider range of solid propellants and composite propellant components. Standards for surface geometry should be formulated in order to provide a convenient parameter for correlating heat transfer effects. For instance, photomicrographs of the surface should be

taken and some characteristic measure of surface porosity, such as bead size-to-void diameter could be used for correlating experimental results.

High speed, close-up photography provides an excellent means for recording the flame spreading phenomenon. Cinematographic analysis has provided evidence of important heat transfer effects (Fig. 3), and it is anticipated that a sensitive parameter to study would be the propellant surface temperature. Hence, additional instrumentation for advanced studies should include rapid response heat flux gauges to measure the heat transfer history produced at the propellant surface as it is engulfed by the spreading flame. In addition, the propellant surface could be heated by thermal radiation or cooled by refrigeration, with miniature thermocouples (Reference 10) imbedded in the surface to produce an accurate measurement of the temperature history during exposure to the spreading flame. Results of these measurements should reveal the proper unsteady-state surface vaporization boundary condition, and provide the stepping stones to an exact quantitative treatment of the problem.

In practice, rocket motor ignition takes place at elevated pressures, typically from 50 to 500 psi. In order to determine whether the highly significant effects of surface geometry, causing a marked increase in flame spreading velocity, are also present in this range of pressures, it is proposed that an apparatus be fabricated which is suitable for testing in this range. If surface geometry effects can be exhibited in the range of actual motor igniter performance, it may be possible to design more efficient ignition systems.

Forced convection of hot, combustion gases past the propellant surface occurs in actual rocket motors and significantly affects the flame propagation. Any study of flame spreading must ultimately include these effects and future investigations should lead in the direction of dynamic flow experiments where the flame spreading velocity may be measured as a function of gas velocity, gas temperature, chamber pressure, etc. This would constitute an overall analysis of the problem, but at present it is felt that more fundamental investigations, as described above, be performed and these results understood before the overall problem is approached.

The present study was conducted under quiescent conditions, using a simplified physical model, and the results indicate a highly complex, two-dimensional mode of flame spreading involving influential heat transfer effects. The continued investigation of the relative importance of the several fundamental parameters governing the flame spreading phenomenon should eventually make it possible to produce an exact analysis of this important phase of solid rocket motor ignition.

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APPENDIX

ONE-DIMENSIONAL MODEL OF FLAME SPREADING

Presented herein is the simplified, gas-phase theory of flame spreading developed in this laboratory to describe this phenomenon on a fundamental level.

Assumptions:

- (1) The distance ahead of the flame which is affected by the presence of the approaching flame (thermal layer thickness) is assumed constant.
- (2) A temperature runaway leading to ignition takes place in the gas phase at a distance, X_{1g} , above the surface (assume X_{1g} is constant).
- (3) Assume that the concentration of the test gas is unaffected by the diffusing propellant vapor.
- (4) From the diffusion equation, after Crank (Reference 11), assume that the diffusing vapor concentration at X_{1g} is proportional to t^n , where t is the time and n is a positive constant.
- (5) The reaction between propellant vapors and test gas is second order.
- (6) Neglect heat transfer in the gas phase, so that the quantity, Q_{chem} , the heat generation/ unit mass is the only source of heat generation to

the surface.

The energy equation governing the heat flow in the gas near the surface at the site of ignition becomes:

$$\rho C_p \frac{\partial T_g}{\partial t} = Q_{chem} \quad (1)$$

where:

ρ is the density (mass/unit volume)

C_p is the heat capacity/unit volume

The chemical heat generation rate per unit mass, Q_{chem} , for the postulated second order reaction may be represented as:

$$Q_{chem} = q_f (C_f)_{ig} C_g A_g e^{-E_g/RT_g} \quad (2)$$

where:

q_f is the heat of combustion of the fuel/unit mass

$(C_f)_{ig}$ is the fuel vapor concentration at the site of ignition in the gas phase (mass/unit volume)

C_g is the test gas concentration (mass/unit vol.)

A_g is the Arrhenius pre-exponential factor
(mass/unit volume)⁻²/unit time

E_g is the activation energy for the gas phase reaction

T_g is the gas temperature

R is the universal gas constant

For X_{1g} a constant, $(C_f)_{X_{1g}}$ is proportional to t^n (Reference 11), where n is a positive constant, and hence, Q_{chem} is a function of time only.

Rewriting Eq. (2),

$$Q_{chem} \propto q_f (s_g t^n) C_g A_g e^{-E_g/RT_g}$$

and noting that $C_g = Z_g s_g$ where Z is the mole fraction,

$$Q_{chem} \propto q_f s_g^2 Z_g t^n A_g e^{-E_g/RT_g} \quad (3)$$

Substitution of Eq. (3) into the energy equation (1) yields:

$$s_g C_p \frac{\partial T_g}{\partial t} \propto q_f s_g^2 Z_g t^n A_g e^{-E_g/RT_g} \quad (4)$$

Assuming perfect gas behavior, $s_g = P/RT_g$

where P is the surrounding gas pressure level, Eq. (4)

may then be written as:

$$\left[\frac{RC_p T_g}{q_f A_g e^{-E_g/RT_g}} \right] \frac{\partial T_g}{\partial t} \propto Z_g P t^n \quad (5)$$

Since q_f , A_g , and E_g are physical constants, the expression in brackets is a function of T_g , only.

This simple first order differential equation may be integrated between temperature limits of T_{1n} and

T_{ig} , and over a time interval 0 to t_{ig} , or τ .

where:

T_{in} is the initial gas temperature

T_{ig} is the "ignition temperature"

τ is the ignition delay

Eq. (5) becomes, following integration and substitution of limits:

$$F(T_g) \Big|_{T_{in}}^{T_{ig}} \propto Z_g P \tau^{n+1} \quad (6)$$

The expression on the left depends only upon the initial and final gas temperatures and the several physical parameters involved in the Arrhenius Law, all of which may be assumed constant.

Therefore if P remains constant,

$$\tau \propto Z_g^{-\frac{1}{n+1}} \quad (7)$$

and if Z_g is constant,

$$\tau \propto P^{-\frac{1}{n+1}} \quad (8)$$

However, since the thermal layer thickness is constant,

$V \propto \frac{1}{\tau}$ and substitution of Eqs. (7) and (8) into this relation yields:

$$V \propto P^{\frac{1}{n+1}} \quad \text{where } n > 0$$

This simplified analysis; i.e., one-dimensional, neglecting heat transfer effects at the gas phase reaction site predicts pressure exponents less than unity.

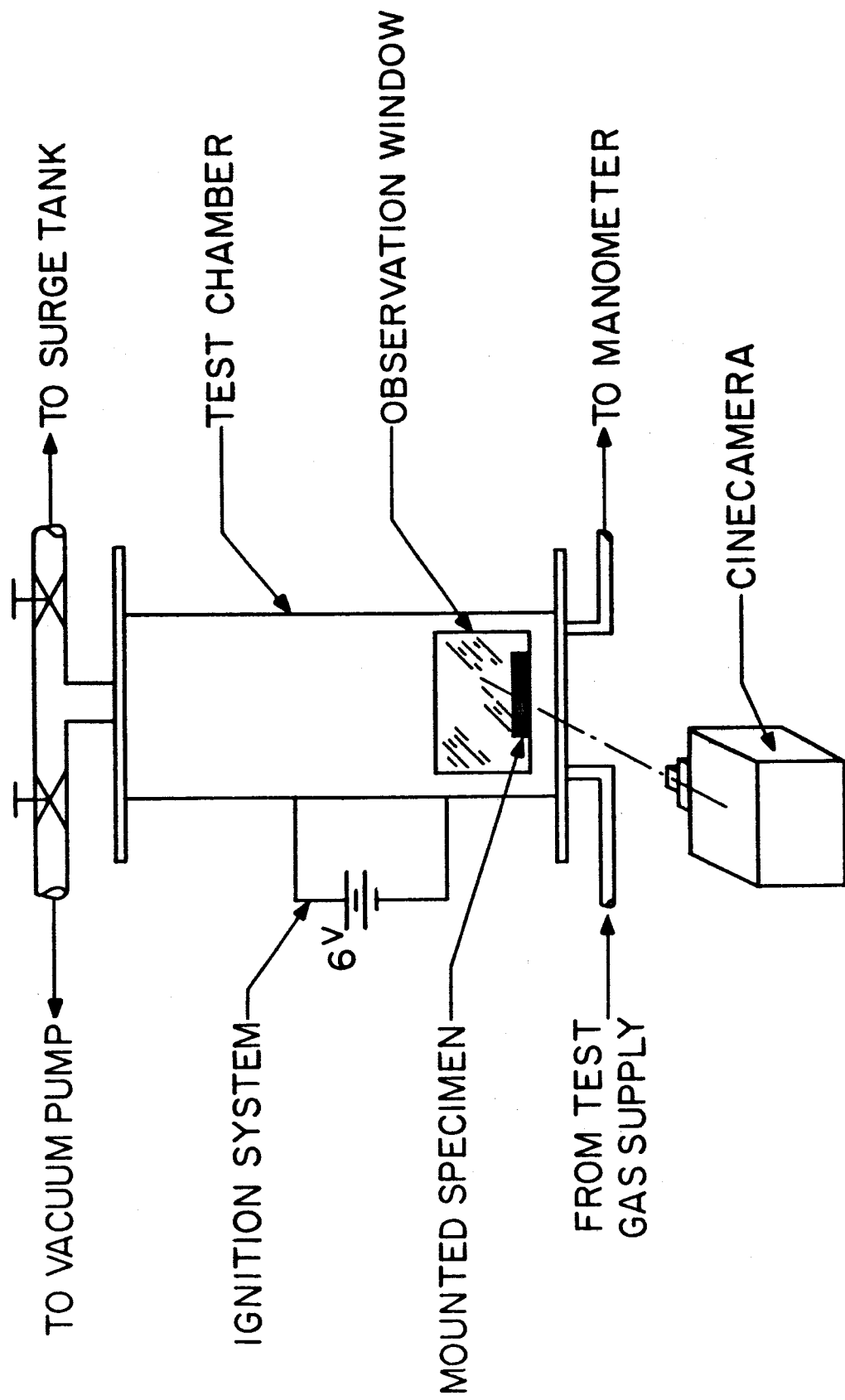
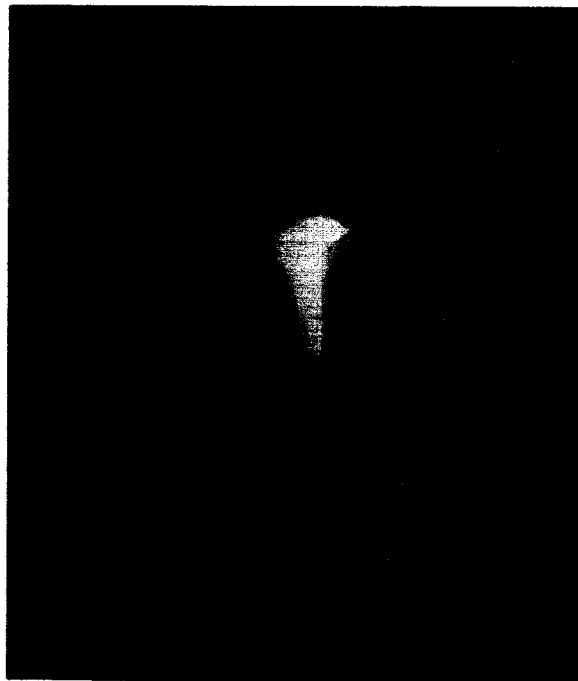
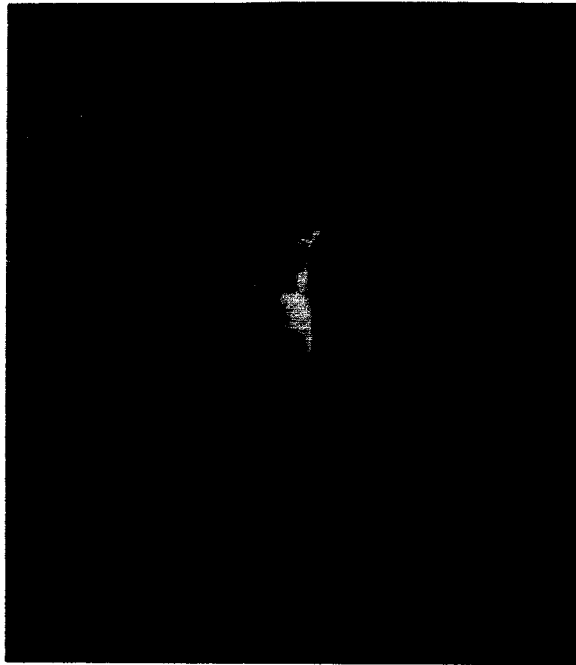


FIG. 1. SCHEMATIC OF APPARATUS FOR FLAME SPREADING VELOCITY MEASUREMENT



PMM SPECIMEN



PS SPECIMEN

FIG. 2 FLAME SPREADING OVER IGNITING SOLID THERMOPLASTIC SURFACES IN 100% OXYGEN ENVIRONMENTS



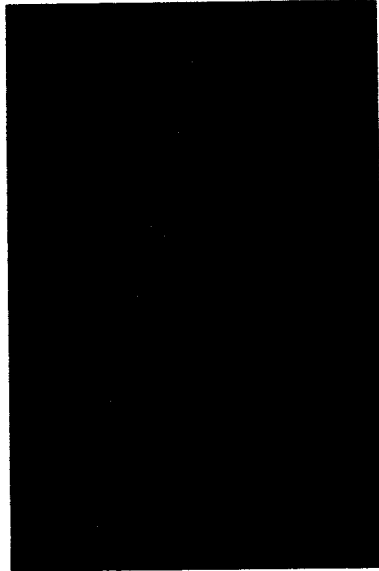
FRAME 1



FRAME 2



FRAME 5



FRAME 10

FIG. 3 STAGES OF FLAME SPREADING OVER A POLYSTYRENE
BEAD SURFACE

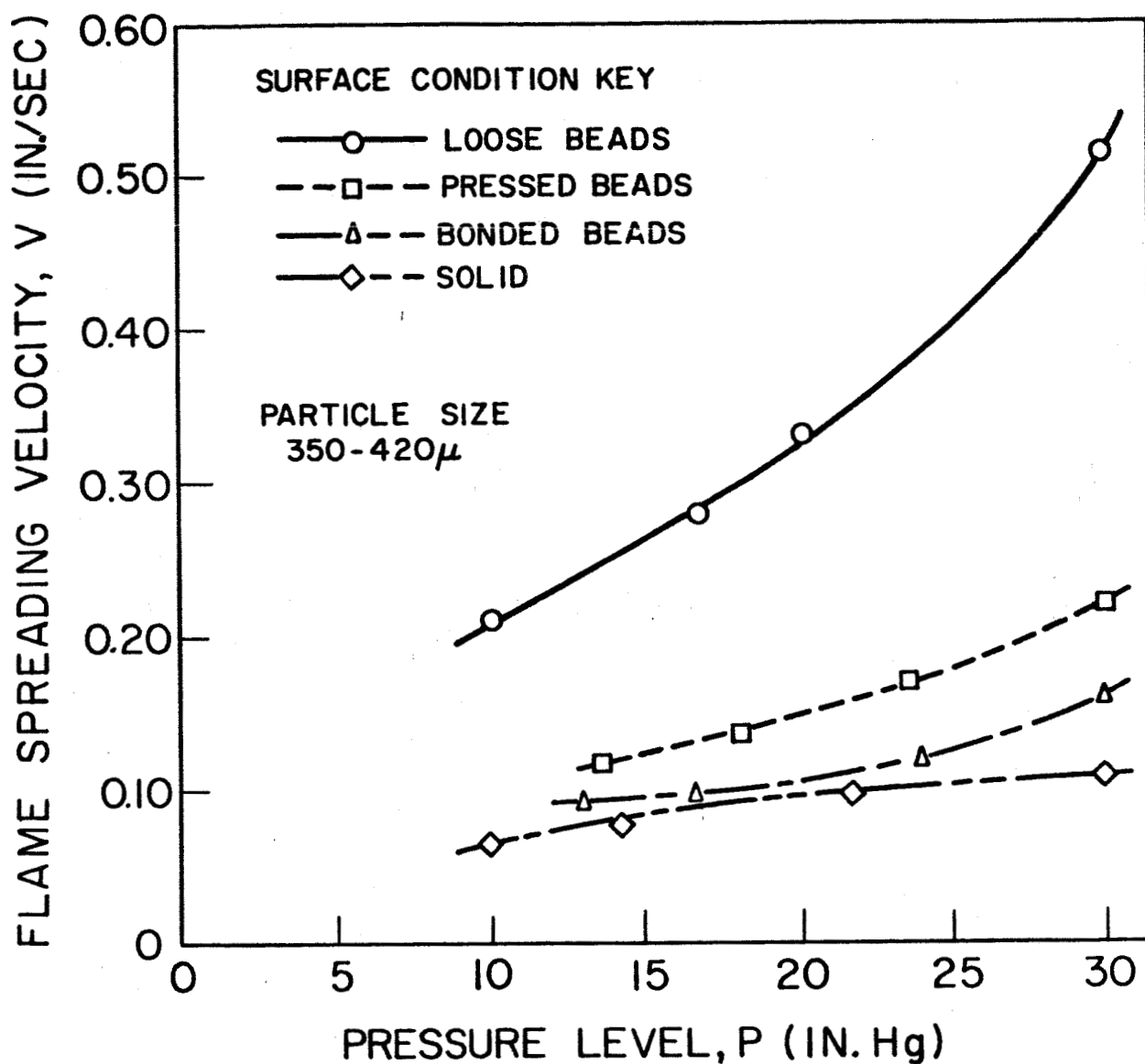


FIG. 4 EFFECT OF PRESSURE LEVEL ON FLAME SPREADING VELOCITY FOR POLYSTYRENE SAMPLES IN 100% OXYGEN AS A FUNCTION OF SURFACE CONDITION

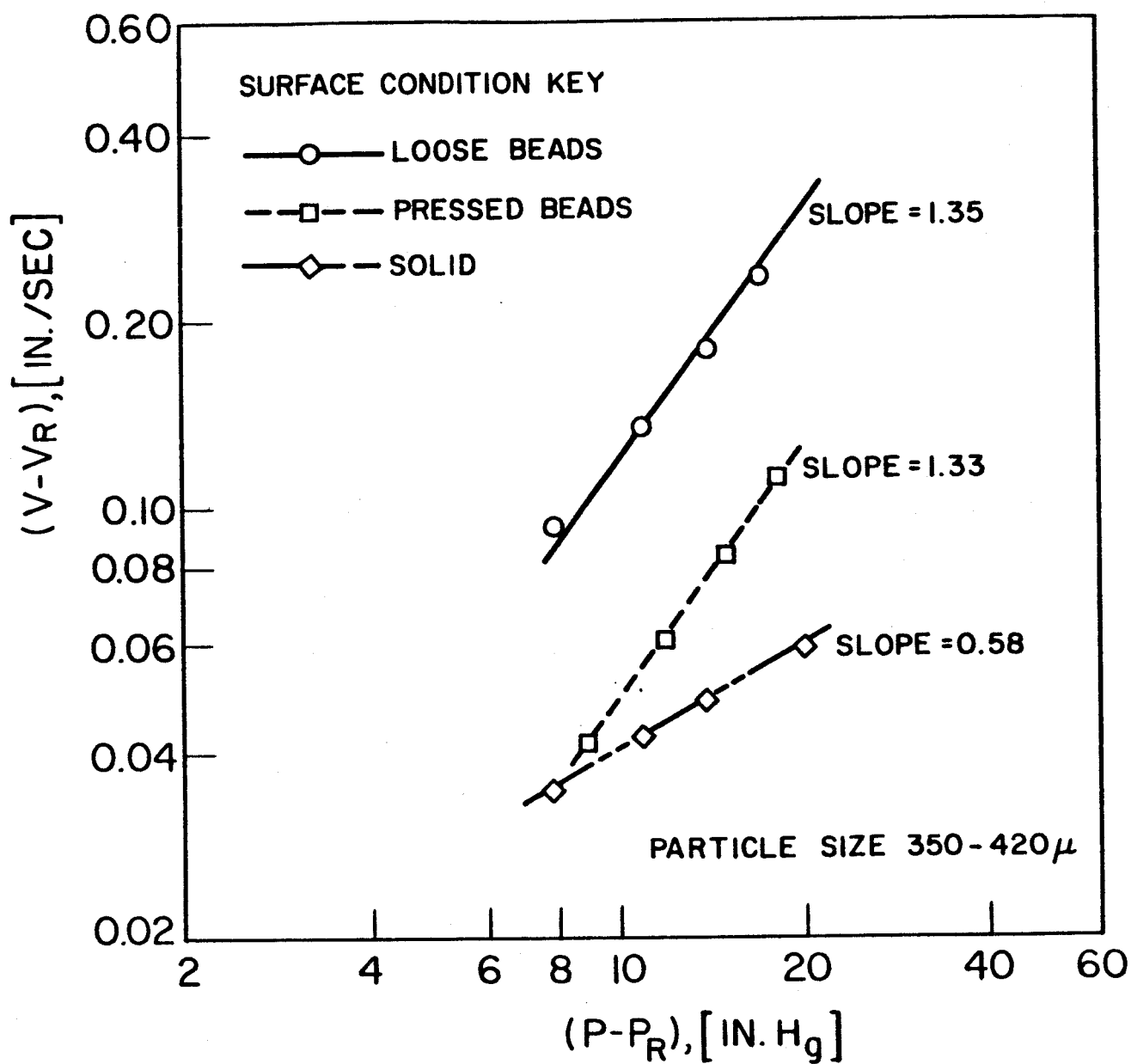


FIG. 5 LOG-LOG PLOT OF $(V-V_R)$ VS $(P-P_R)$
FOR POLYSTYRENE SAMPLES IN
100% OXYGEN

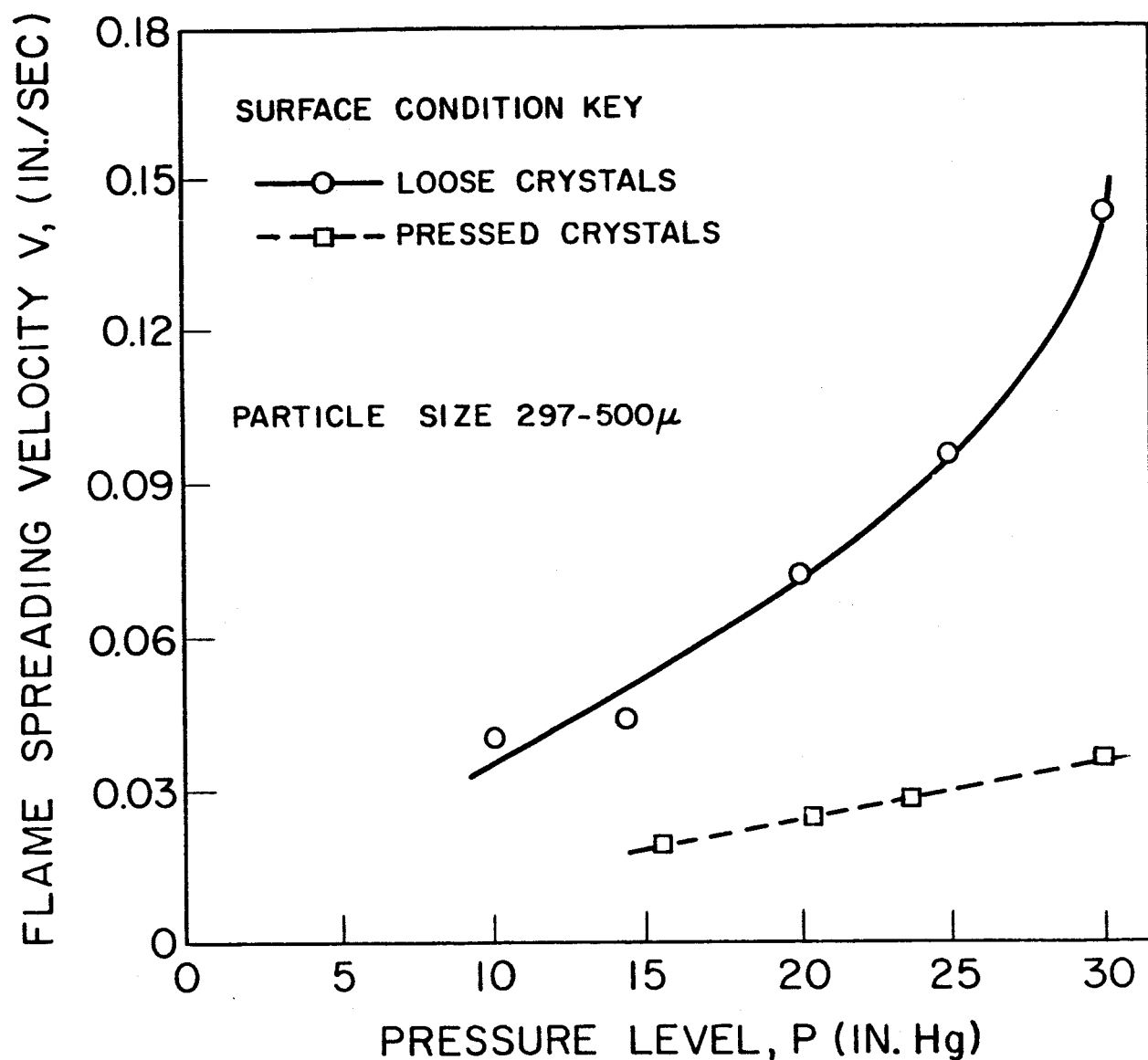


FIG. 6 EFFECT OF PRESSURE LEVEL ON FLAME SPREADING VELOCITY FOR AMMONIUM PERCHLORATE SAMPLES IN 100% METHANE AS A FUNCTION OF SURFACE CONDITION

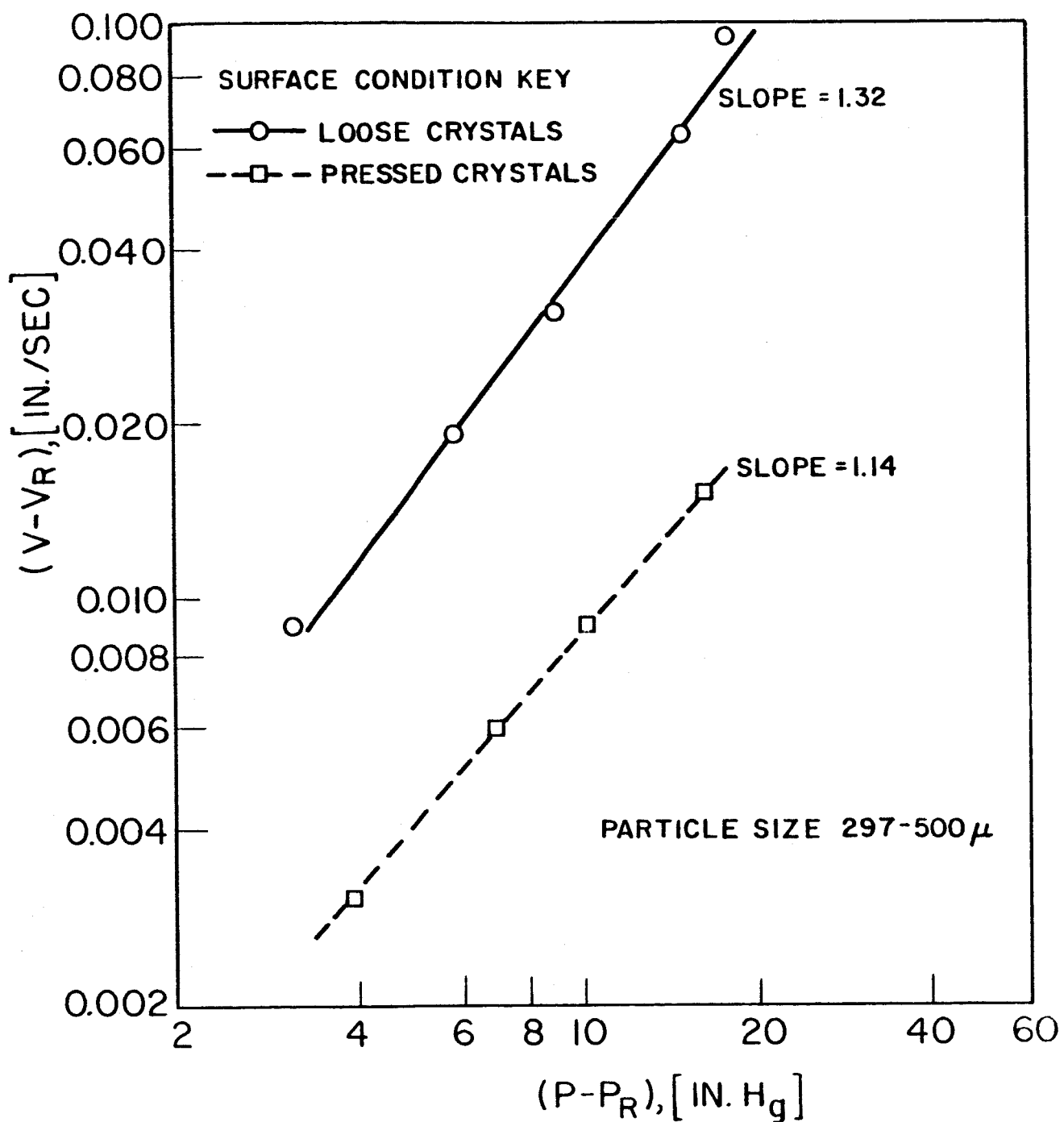


FIG. 7 LOG-LOG PLOT OF $(V-V_R)$ VS $(P-P_R)$
FOR AMMONIUM PERCHLORATE
SAMPLES IN 100% METHANE