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THE ROLE OF BLACK POWDER IN PROPELLING CHARGES

Forman Williams

Picatinny Arsenal
Dover, New Jersey

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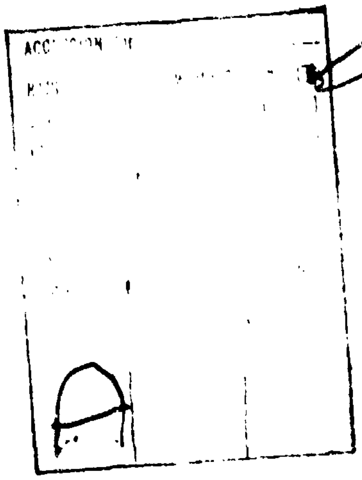

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A study is reported on the role of black powder in propelling charges. From the literature it is established that although detailed scientific studies of black-powder combustion have been made, many key aspects of the burning mechanism remain unknown. Results of high-speed photography of particles of black powder, ignited by a pulsed laser, by a spark and by a heated wire, are reported and employed to infer that during burning the material emits small particles of hot salts that

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travel at velocities as high as 5000 cm/sec. It is also inferred from the film strips that continuous spread of flame along the surface of a black-powder particle is relatively slow. Scanning electron micrographs of quenched samples of burning black powder are exhibited to show the presence of a melt layer on the surface. It is reasoned from existing evidence that in a propelling train heat from the percussion initiator ignites the black powder, that the black powder ignites the main propellant by providing heat probably principally through impingement of hot salt particles and that the major role of black powder in the train is likely to be provision of rapid flame spread, resulting quickly in multiple ignitions of the main propellant. A gas-dynamic model for flame spread through black powder is developed, and its predictions concerning flame-spread histories and primer delay times are presented. An alternative flame-spread model, believed to contain the main aspects of reality, is proposed, in which hot salt particles are viewed as taking a random walk through the powder matrix, with multiplication of particles at each step. A tentative design for a closed-bomb experiment is proposed for testing performance of black powder under closely use-related conditions. The design involves use of ionization gauges to monitor flame spread along the primer. It is also recommended that flame-spread experiments at atmospheric pressure be investigated as a possible inexpensive test for black-powder product assurance.

Foreword

Plans for converting from batch processing to automated, primarily continuous production of black powder, involving among numerous changes, replacement of the traditional wheel mill by a jet mill, have raised concerns over the possibility of consequent modifications in performance of black-powder primers for propelling charges. As a step in preparing to test the performance of the material produced by the new process, the Product Assurance Directorate asked the author to investigate the role of black powder in ignition trains, to review literature on its ignition and burning mechanisms, to propose a mechanism for its participation in the ignition sequence, and to suggest a performance-oriented laboratory test that eventually might be employed as a basis for product acceptance. The present report details the results of this investigation.

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The author is particularly indebted to J. Craig Allen of the Product Assurance Directorate, Picatinny Arsenal for providing a large body of information, needed in pursuing this study.

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1. INTRODUCTION

Black powder is employed as the propellant for the primer in many propelling charges. Although it is the oldest propellant known to man, in a number of primer applications, no materials have been found which exceed it in performance. The reasons underlying the high performance of black powder in specialized applications remain obscure today. This state of affairs is not due to lack of scientific study — on the contrary, in the next section it will be seen that since antiquity, the material continually has been subjected to close scientific scrutiny. Instead, the current ignorance stems from the extreme complexity of the combustion mechanism. This complexity precludes detailed analysis and necessitates utilization of merely qualitative concepts in studying the role of black powder in propelling charges.

Black powder is a mixture of saltpeter, charcoal and sulfur in a ratio (weight percentages of about 75, 15 and 10) that corresponds almost exactly to stoichiometry for the reaction

$$2\,KNO_3 + 3C + S \rightarrow K_2S + N_2 + 3\,CO_2 \ . \qquad (1)$$

Thus, the powder itself is composed of three distinct solid phases, and to react the materials from these three phases must find some way to intermingle molecularly. Because of this multiphase constitution it is mildly surprising that the material will even deflagrate, let alone detonate (which it clearly does, in view of the periodic disappearance of its manufacturing facilities as a consequence of violent explosions). Intermingling is encouraged by blending finely divided particles of each phase into the final product, with constituent particle sizes falling between 1μ and 100μ on the average. The blend is pressed into cakes which are ground into sized pellets (a mean diameter of roughly 3000μ for class 1 to roughly 300μ for class 5) that are glazed with graphite. Measured products of combustion of pellets do not coincide with the right-hand side of Eq. (1) but instead include a variety of species, among which are NO, NO_2 and K_2SO_4.

The doner-receiver relationships of black powder to its primer and also to the main propelling charge can be described qualitatively, with a reasonable probability of truth, on the basis of what already is known concerning the combustion mechanism, as supplemented by a few new experimental observations that were made in connection with the present study. Simplified models for the role of black powder are developed herein on the basis of this qualitative description, but specifics of the models can be verified or disproven only through comparisons with future experiments. Section 3 contains these new experimental and theoretical results, preceded by an exposition of our current understanding of burning and flame-spread mechanisms for black powder.

A consequence of the investigation reported in Section 3 is the conclusion that modifications of black powder which may arise through changes in manufacturing procedures, conceivably could affect the primer performance without causing the product to fail to pass current specifications. This underlines the desirability of developing a performance-oriented acceptance test for black powder. One concept on which such testing may be based is given in Section 4, where a preliminary design for an experiment is presented.

The conclusions of the study and its recommendations are summarised succinctly in Sections 5 and 6.

2. LITERATURE

2.1 Studies of Black Powder Prior to the Twentieth Century

The first propellant discovered by mankind was black powder. It is impossible to pinpoint the date and location of the discovery, which may have been made more than 2000 years ago. Most accounts place the discovery in China, although Greece also is a possibility. An arabic book written in 1250 describes properties of black powder (see Ref. 1). The material was so useful in warfare that with the rebirth of learning scientific study of its characteristics commenced with intensity. Benjamin Robins attributes De la Hire with writing the first modern paper on black powder in 1702.[2] The early concern centered around the peak pressure and force that black powder could generate when ignited in the barrel of a gun. A point of contention was whether combustion ceased prior to motion of the shot, and the affirmative answer of Robins[3] was more nearly correct than the opposite conclusion of a Royal Committee.

Chevreul[4] was aware of the stoichiometry given in Eq. (1). Only later[5, 6] did detailed information become available on the actual products of combustion. Methods for studying the impulse produced by black powder, that were quite ingenious for their time, were developed in England,[7, 8] Prussia,[9] Moscow,[10] Boston[11] and France.[12] Ideas, for example, of observing shots from small side barrels to obtain force histories were applied. The most authoritative text of the nineteenth century appears to be that of Piobert.[13] The most thorough of all early scientific studies probably is found in the work of Noble and Abel,[6] who literally covered from A to Z all questions concerning black powder and its performance in guns.

2.2 Studies of Black Powder in the Twentieth Century Prior to 1960

Interest in black powder began to wane in the twentieth century due to the gradual assent of smokeless powder, invented by J. F. E. Schultse in Germany in 1867. By the turn of the century, most small arms were based on smokeless powder, as developed by Vieille, and by the early 1930's smokeless powder had replaced black powder even in rockets. Nevertheless, the specialized uses for black powder remained, and periodically its properties were studied scientifically by new techniques, as they became available. Especially notable is the study of Blackwood and Bowden,[14] which is more relevant to the problem considered herein than is any other work.

Blackwood and Bowden[14] report many pertinent observations on initiation, thermal decomposition and flame propagation of black powder.

For initiation they ascribe importance to the facts that the melting points of sulfur and of potassium nitrate are approximately 120°C and 330°C, respectively. They adopt the reasonable view that for reaction to begin at least one of the components must melt and flow to achieve close molecular contact with another component. The observation that grit addition enhances impact ignition only if the melting point of the grit exceeds that of sulfur is interpreted as suggesting that melting and flow of sulfur alone can produce ignition at sufficiently high pressures. At lower pressures, in the vicinity of atmospheric, the fact that the heated-plate ignition temperature lies between 300 and 350°C may be interpreted as suggesting that some melting of potassium nitrate is required. In any event, the idea that ignition occurs at a local hot spot within the powder is well substantiated.[14]

Thermal decomposition was studied by measuring rates of gas evolution under isothermal conditions of elevated temperature, for black powder as well as its constituents, separately and in pairs.[14] These observations, coupled with measurements of product composition, led Blackwood and Bowden to propose a reaction mechanism that was consistent with these results and also with initiation measurements. Important steps in the initiation mechanism were suggested to include

$$2\,KNO_3 + S \rightarrow K_2SO_4 + 2\,NO \quad , \tag{2}$$

$$KNO_3 + 2\,NO \rightarrow KNO_2 + NO + NO_2 \quad , \tag{3}$$

$$2\,NO_2 + 2S \rightarrow 2\,SO_2 + N_2 \tag{4}$$

and

$$2\,KNO_3 + SO_2 \rightarrow K_2SO_4 + 2\,NO_2 \quad , \tag{5}$$

as well as reactions involving H_2S formed from organic constituents of charcoal. Steps (4) and (5) might be viewed as a chain, with NO_2 and SO_2 as carriers and with step (3) as the initiation process. Steps (2) and (5) are exothermic, while the others shown are endothermic. Hot potassium sulfate (melting point 1080°C) was a major condensed product, formed directly by step (2) and also through the sequence (3), (4) and (5).

Streak and high-speed framing photography provided a considerable amount of revealing information on flame propagation in black powder.[14] At atmospheric pressure the normal regression rate of a burning pellet 2 mm in diameter was observed to be only about 0.4 cm/sec, while the spread (propagation) rate through a collection of particles was approximately 60 cm/sec. Under confinement where pressure could build up, the spread rate measured by streak photography reached about 2000 cm/sec at an estimated pressure of 40 atm. Framing photography of sparse arrays and analysis of "smoke" deposits on glass strongly suggested that spread was produced by traveling hot sprays of molten salts, with melting temperatures between 550 and 750° C and with particle sizes ranging from less than 1μ to more than 10μ. Fragments burning only on one side also could be propelled to produce spread. This rapid spread is not observed in black powder composed of fine particles (< 100μ in diameter) when they are packed in close contact; in this case propagation resembles normal regression of the larger pellets. It seems logical that hot salts containing K_2SO_4 are the agents in rapid spread.

The other twentieth century study prior to 1960, worthy of explicit mention, is the modern thermoanalysis of Campbell and Weingarten.[15] Differential thermal analysis and thermogravimetric analysis of black powder and mixtures of its components, similar to those of Blackwood and Bowden, yielded overall activation energies for initiation in the vicinity of 14 kcal/mole, except in the absence of sulfur, in which case the activation energy increased to roughly 30 kcal/mole. The results lend support to the mechanism given in Eqs. (2) through (5) and also suggest that Blackwood and Bowden tended to overemphasize the importance of reactions of sulfur with charcoal organics.

2.3 Soviet Studies of Black Powder in the 1960's

Twentieth-century studies of black powder were pursued in non-English speaking countries as well (e.g., Ref. 16). The Soviet Union maintained an interest in the subject and kept abreast of Western developments.[17] From a recent Soviet text[18] it may be seen that the Russians mounted a detailed scientific study of the normal regression rate of black powder in the 1960's. This information contributes peripherally to the present study and therefore is worthy of review here.

Detailed measurements of the normal regression rate of black powder were made at reduced,[19] elevated[20] and very high[21] pressures. The results are shown in Fig. 1. It is seen that the pressure exponent of the burning rate decreases as the pressure increases. Although the exponent appears to approach unity at very low pressures, the rate depends only very weakly on pressure at high pressures. An increase in pressure by four orders of magnitude produces a rate increase of barely one order of magnitude. Although different segments of the curve can be assigned different slopes to suggest the existence of transition pressures at which the slope changes abruptly, the data in total are equally consistent with the illustrated continuous variation in slope. From earlier work such as that of Blackwood and Bowden, it is known that the burning mechanism of this heterogeneous material will have to be complex and that therefore a theoretical explanation of the results in Fig. 1 will be difficult to obtain.

Soviet theoreticians attempted to analyze the normal regression of black powder in an effort to predict theoretically the data of Fig. 1.[22-25] Especially noteworthy is the final paper of Novozhilov on the subject.[25] All of these studies adopted a model of the same general form, one which physically seems quite reasonable for black powder. In normal regression, the conditions of interest in the primary heat-release zone correspond to much higher temperatures than those existing during initiation. At these very high temperatures, it seems reasonable to assume that sulfur, potassium nitrate and their products of reaction are gaseous. Since carbon is highly nonvolatile, a hot reaction-zone model in which carbon particles burn in a gaseous oxidizer becomes very appealing. The carbon is viewed as being swept off the surface into the gas by vaporization of sulfur and potassium nitrate. A two-phase flow model, with reactions on the surface of the carbon particles, was developed for the hot combustion zone.[22, 23, 24] Assuming that the carbon reactions are diffusion-controlled, the investigators showed[23] that the predicted burning rate is proportional to $\sqrt{p/d}$, where p is pressure and d is the diameter of the carbon particles. It is seen that this result does not agree very well with the data in Fig. 1. Moreover, the magnitude of the predicted burning rate is well below that observed experimentally.[25] This strongly suggests that although appealing, the Soviet model is inappropriate for predicting the burning rate of black powder. The rate may be controlled by processes that occur at lower temperatures and that do not involve carbon combustion in an essential way.

2.4 Applications for Black Powder in Propelling Charges

There are numerous use-oriented publications that provide information on black powder.[26-29] Knowledge of the structures of propelling trains[30, 31, 32] aids in understanding the role of the material. Further significant detailed information is provided by drawings[33-37] of elements of important components for the 105 mm round. It becomes clear that the function of the M61 percussion primer is to ignite the black powder charge of the M28B2 primer, which in turn ignites the M1 propellant of the M67 main propelling charge. Thus, black powder serves as an intermediate in the propelling train.

In the M67 it is contained within a metal primer tube approximately 1 cm in diameter and 25 cm long, positioned axially along the entire length of the propelling charge. The tube is perforated, containing four rows of eleven holes 0.35 cm in diameter, thereby allowing communication between the black powder and the main charge. A nitrated paper bag prevents the nominally 2mm black-powder pellets from passing through the perforations in the assembly. The M61 initiator fits into one end of the primer tube in such a way that the percussion-ignited initiator propellant is directed onto the black powder.

From these observations it seems logical that the purpose of the black powder is to provide quickly multiple ignition sites in the main propellant. Apparently it does so by spreading the flame quickly along the black powder itself and by quickly igniting the main charge adjacent to it. The rapid flame-spread properties of black powder, elucidated by Blackwood and Bowden,[14] distinguish this material from other propellants and probably are responsible for its retention in a specialized primer role in propelling charges. This reasonable hypothesis underlies the developments to be presented in subsequent sections.

2.5 Assurance of Performance of Black Powder

Numerous controls exist for assuring that propelling charges and their components function properly.[38, 39, 40] There are also very definite specifications for black powder,[41] its constituents[42, 43, 44] and primer components associated with it.[45, 46, 47] In spite of these standards, problems with the functioning of black powder have arisen from time to time. For example, performance problems with Austin powder were traced[48, 49] to excessive tumbling (the process in which the finished powder is graphite coated). This illustrates that problems can arise even when existing specifications are met. Perhaps to help forestall such problems, a use-oriented combustion test was inserted into black-powder specifications (Section 4.4.10, Amendment 3 of Ref. 41); static firings of primers were to be performed and the residue checked for completeness of black-powder combustion. However, this element of black-powder specifications has now become inoperative.

Under certain situations, existing specifications appear to be quite adequate. For example, for many years military black powder was produced by the Dupont process in a single facility, and with this fixed manufacturing procedure irregularities readily would appear through nonconformance with specifications. Added concern must arise when new manufacturing procedures are contemplated. For example, with nitrocellulose-based propellants worries associated with adoption of continuous processing prompted studies[50, 51] of methods for quality assurance of the propellant.

Plans are underway to replace the Dupont process for manufacturing black powder by a basically continuous process, because of many desirable attributes of the new process.[52, 53] However, as might be expected for a product as complex as black powder, such a radical change in processing introduces definite differences in certain properties of the final product,[53, 54] properties that are not addressed in the existing specifications.[54] Thus, the mean particle size of pellet constituents is approximately 15 μ for Dupont powder but only about 5 μ for the new product.[54] The degree of agglomeration of particles composing pellets also may differ for the two processes.[54] If, as suggested earlier, travel of burning particles dislodged from pellets contributes to flame spread, then clearly the new process potentially could modify performance, although it is unclear whether the modification would be beneficial or detrimental. An objective of the present study is to search for means of detecting detrimental modifications.

2.6 Picatinny Research on Black Powder

Concerns over black powder have prompted continuing research on combustion of the material at Picatinny Arsenal.[55, 56, 57] Much of the work has been thermochemical, and considerable evolution has occurred in design of a calorimetric bomb for measuring heat release in addition to force and relative quickness. More complete simulations for gun chambers in closed-bomb experiments also have been achieved.[58, 59] Thus, there exists background information pertinent to design of use-oriented acceptance tests. References 50 and 51, as well as the in-house Picatinny studies, are relevant to such testing.

An interesting study of black-powder performance recently has been reported in Ref. 60. The ignition delay in a propelling charge was reduced by a factor of two by changing from roughly 2mm to roughly 300 μ sized pellets and by modifying the black-powder primer configuration. The study is revealing in two respects. First, a small increase in the rate of flame spread was achieved in substituting the finer pellets. Although this may appear to be contrary to the observation of Blackwood and Bowden to the effect that spread through fine powder is very slow, the fact that the 300 μ particles are appreciably larger than the fine powder of Blackwood and Bowden implies that there is no contradiction. The result suggests that very fine and very coarse particles both exhibit slow spread rates, there being an optimum particle size, in the vicinity of a few hundreds of microns, for maximum rate of spread. Secondly, the reduction in ignition delay was appreciably greater than the increase in spread rate, thereby suggesting that flame spread is not the only function of black powder. Production of multiple ignitions of the main charge appears to be an additional important function. Increased quickness apparently can result from an increased number of ignitions without there being an increase in spread rate through the black powder itself, under suitable conditions.

3. MODEL FOR THE IGNITION SEQUENCE

3.1 Current Understanding of Burning and Flame-Spread Mechanisms for Black Powder

As indicated at the end of Section 2.4, flame spread, in its broadest sense, appears to be the role of black powder in propelling trains. The powder receives from the percussion primer heat which serves to ignite it, and the powder itself spreads flame to the main propellant, quickly producing a large number of ignition points within the propellant. This mode of functioning appears also to be consistent with the observation reported at the end of Section 2.6, in the sense that spread of ignition to multiple points of the main propellant is an important part of the black-powder flame-spread function. The models treated herein assume that flame spread is the important function that black powder must fulfill.

Current knowledge of burning and flame-spread mechanisms of black powder has been summarized in Sections 2.2, 2.3 and 2.6. There is information concerning the ignition mechanism of black powder even at the level of kinetic mechanisms; melting of sulfur and of potassium nitrate is known to be involved, and data on quantities such as ignition temperatures are available (Section 2.2). The situation concerning normal regression is that rate data is available but a proper theoretical understanding is lacking (Section 2.4). Spread is known to involve transport of hot condensed salts and possibly burning fragments (Section 2.2). Since spread is so critical, additional experimental observations relevant to the subject have been completed in connection with the present study. These experiments will be summarized before the models are discussed.

3.2 New Experimental Observations on the Burning of Black Powder

A few tests of combustion of black powder were made in an apparatus available from research supported by AFOSR (monitored by B. T. Wolfson), using black powder provided by J. Craig Allen (Class 1, sizes in the vicinity of 0.5 to 3mm, Dupont lot no. 75-88). Also used for comparison purposes was a nondescript, commercially available smokeless powder (H110), as well as both carbon and magnesium particles. Some of the black powder pellets were crushed to provide particles in the size range of 100 to 500μ; the same as the size range of the smokeless powder, carbon and magnesium particles.

Three types of ignition were employed, viz., laser ignition, spark ignition and ignition by a heated wire. In the former case, a pulsed neodymium glass laser was employed, whose maximum output was on the order of 1 joule, delivered in 0.2 msec. The laser-ignition experiment is quite similar to that first described by Wilson,[61] although the laser is the one used by Law.[62] The apparatus is shown schematically in Fig. 2. All tests were performed in air at atmospheric pressure. A particle is suspended on a fine glass fiber in the focal plane of the laser and of a high-speed framing camera. A timing circiut triggers the camera, backlighting and the laser, and the burning sequence is recorded photographically, at framing rates between 5000 and 20,000 frames per second.

A number of sequences of laser firings are shown in Fig. 3. On all film strips the light markings on the left-hand side occur at 1msec intervals, and the magnification is 0.72 on 16 mm film. The wavelength of the laser is such that it does not expose the film. The first two strips show that a slight glow of the glass probe is produced by heating from the laser pulse. The next two show that a carbon particle of the type used by Ubhayakar[63] is heated more strongly and may in fact exhibit a small amount of gas-phase combustion during the laser pulse; after cessation of the pulse the particle merely cools. In the fifth strip it is seen that a 500μ black powder particle burns violently during the laser pulse but extinguishes thereafter. Similar behavior is exhibited for the larger (2mm) ans smaller (200μ) particles of black powder in the sixth and seventh sequences. The magnesium in the eighth strip burns to completion under the same ignition impulse. By varying the degree of backlight in the final two strips, the flame and particle, respectively, are accentuated for black powder. In all cases the black powder particle moves off in a direction opposite from the side on which the laser light impinged, i.e., the burning side of the particle.

It is of interest to compare the behavior of black powder with that of smokeless powder. A blowup of a film strip for smokeless powder is shown in Fig. 4. It is seen that the burning is much more spherically symmetrical but that again extinction occurs upon cessation of the laser pulse. This in fact is to be expected from earlier work on radiant ignition.[64] If the ignition pulse is too intense or too short, extinction occurs (by "deradiation") upon cessation of the pulse. In the present experiment, conditions lie well within the range of deradiative extinction for smokeless powder. Apparently they are also in that range for black powder, although there are no earlier deradiative extinction data on black powder with which this inference can be compared. For magnesium this deradiative extinction does not occur, while for carbon it is known[63] that the atmospheric conditions are such that the particle cannot support combustion in the absence of an external heat source. Diffusion flames may not be subject to deradiative extinction.

Figure 5 shows five sequences for particles of smokeless powder. It may be seen from these sequences that the particle sometimes splits in half and usually detaches from the probe but always extinguishes upon removal of the laser pulse. The flame around the smokeless powder is much smaller than the flame of black powder and contains fewer streaks. Thus, although the smokeless powder readily ignites on all sides, it would appear to be considerably less efficient than black powder in transferring flame to adjacent particles.

Figure 6 shows three backlighted sequences for black powder. The very long one-sided flame during laser irradiation is quite evident for the small particle as well as for the larger ones. Especially for the larger particles, bright streaks that move away from the particle are visible in the frames. These streaks, and the flame, may be seen more clearly without backlighting, as shown in Fig. 7. The streaks must represent tiny but rapidly moving hot particles, possibly burning fragments of the parent particle, or else hot salts.

There are two different ways to obtain meaningful velocities from these figures. One is to measure the initial rate of expansion of the luminous flame away from the particle of black powder. The other is to measure the lengths of the streaks and to divide by the exposure time of the frame(typically on the order of 1/40,000 sec). Both methods give velocities of approximately the same magnitude, on the order of 5000 cm/sec. This is very much larger than the flame-spread velocity (60 cm/sec) measured by Blackwood and Bowden at atmospheric pressure; it even exceeds the spread rate they found (2000 cm/sec) after acceleration under confinement to 40 atm. The velocities obtained here may be interpreted as velocities of motion of individual particles that are responsible for flame spread but not as spread rates, since spread represents an averaged effect of many particles.

It could be argued that the velocities measured are laser produced and are not representative of freely burning black powder. This is unlikely because the laser intensity was kept to a minimum; with a small reduction in intensity the particles failed to ignite.

A third velocity that is easily measured from Figs. 3, 6 and 7 is the velocity of the main particle after cessation of the laser pulse. It is readily apparent that smaller particles attain higher velocities. The velocity attained is a kind of jet-propulsion effect, being produced by the hot combustion products leaving the surface of the particle. Although it could be used to calculate the total impulse produced by these hot products, the result is not likely to be very significant, since it depends on the duration of the laser pulse.

A striking observation is the perpetual maintenance of one-sided burning for black powder. Flame spread along the surface of a black-powder particle appears to be very slow compared with that of a smokeless-powder particle, for example. This suggests that the black-powder spread mechanism within a primer is primarily from particle to particle rather than along the surfaces of individual particles.

Figures 8 and 9 compare scanning electron micrographs of smokeless powder and black powder before and after laser irradiation. It is seen that the smokeless powder initially is quite spherical. After burning its surface becomes pock-marked, suggesting burning with a fluid surface layer and bubbles generated from beneath. By contrast, the crushed black powder is quite angular beforehand, and the high magnification shows that it contains many small crystals of widely varying sizes. After burning the particle appears much smoother, showing definite evidence of liquid formation. The microcrystals are less pronounced but still visible in the high magnification after burning.

Spark ignition was attempted with small particles from crushed black powder, supported on glass probes, in spite of the fact that Blackwood and Bowden report no ignition by a spark. In the sequences shown in Fig. 10, the spark is visible as a sharp, wavy streak; the spark fired repeatedly at irregular intervals. Some smoke and flame was observed occasionally with spark ignition. Although burning was not self-sustained, the black powder can be consumed nearly completely with repeated sparks. The tendency for the particle to move away from the spark, observed by Blackwood and Bowden, also was found to occur often in the present tests.

Hot-wire ignition of non-crushed particles of black powder was produced by the arrangement illustrated schematically in Fig. 11. A pair of stretched wires was used to support the particle away from solid surfaces. One of the burning sequences for this method is shown in Fig. 12. Unlike burning produced by other methods of ignition, in this case combustion of the particle proceeded to completion. Well before completion of burning, the particle drops off its supporting wires and moves out of the field of view of the camera. Point ignitions again are achieved, in this case at a contact between a wire and the particle. The striking phenomenon is the rapid production of a long hot streak of reaction products, emanating from the ignition point. This is similar to the streaks observed with laser ignition. In addition, burning of the particle from the hot spot, with very little spread to the rest of the surface, is characteristic of the combustion process. The results tend to confirm the observations made with laser ignition.

In summary, the present experiments support the idea that black powder is very efficient for producing flame spread by mechanisms that involve direct transfer of hot particles. They also suggest that lateral spread of flame along the surface of a single particle of black powder is slow and under conditions of close packing might be a rate-limiting step.

3.3 A Gasdynamic Model for Flame Spread through Black Powder

If it is agreed that travel of hot salt particles through the black-powder pellet mix is responsible for the flame-spread process, then the problem of predicting the spread rate becomes the problem of predicting the rate of progression of hot particles. The paths that these particles must traverse through the gas is so tortuous that the progression rate cannot be obtained directly from the particle velocities. A difficult statistical problem arises. There is at least one simplifying assumption which bypasses the statistical problem and which may be correct in limiting cases. This is the assumption that, on the average, the hot salt particles progress through the propellant at the same rate as the hot gaseous reaction products. With this assumption, spread rates may be calculated by considering only gas flow, and a gasdynamic model emerges.

It is relevant to ask under what conditions the model may tend to be valid. If the hot particles moved always with the same velocity vector as the local velocity vector of the gas, then the model would be correct. This condition clearly is not attained in the experiment just reported, since the calculated normal gas velocity is less than 500 cm/sec, while the observed particle velocities reach 5000 cm/sec. However, high pressure and small particle size (e.g., small constituent particle sizes in the manufacture of the material, provided that hot salt particle sizes are directly related to constituent particle sizes) tend to favor rapid velocity equilibration between gas and particles, and therefore for suitably produced black powder the assumption may be good at high pressures. Also, it appears that if the packing is very close and the pellets highly irregular, so that the path is quite tortuous, the particles that travel in nearly straight lines and do not follow the gas very often will collide with solid surfaces and therefore make slow progress through the charge, possibly no faster than the gas. Sufficiently high tortuosity and low porosity therefore also can favor the approximation. Nevertheless, it is unclear whether any of these limiting conditions can be achieved in practice. Therefore at present the model must be viewed as speculative.

Consider a chamber of volume V and length L, packed with pellets of black powder such that the void fraction is ϵ (the ratio of the volume not occupied by the powder to the total volume of the chamber). At time $t = 0$ ignition will occur at one end of the chamber, $x = 0$, and flame will propagate through the chamber to the other end, $x = L$. The volume of gas in the chamber, ϵV, is composed of two parts, the original gas (subscript 1) and gaseous reaction products (subscript 2). If it is assumed that the original gas is compressed isentropically, then at any given time its volume is

$$V_1 = \epsilon V(p_0/p)^{1/\gamma} , \tag{6}$$

where p is chamber pressure, p_0 the initial pressure and γ the specific heat ratio for the original gas. Neglecting the decrease in pellet volume during the spread process (a reasonable approximation), the volume occupied by product gases will be

$$V_2 = \epsilon V - V_1 . \tag{7}$$

The product gases are treated as ideal, with mean molecular weight $\overline{W}_2$ and flame temperature T_2. Here both of these quantities will be treated as fixed constants. The poorest approximation is constancy of T_2, which will increase as p increases and be different for different elements of the product gas. However, estimates on adiabatic compression suggest that the approximation will be reasonable perhaps up to a pressure of the order of 100 atm. With the given approximations, the density of the product gas is

$$\rho_2 = p\,\overline{W}_2/R^\circ T_2 , \tag{8}$$

where R° is the universal gas constant.

The mass of the product gas is $\rho_2 V_2$, and the time rate of increas of this mass is determined by the burning rate. Let m be the normal burning rate (mass per unit area per second) of a particle of black powder. This quantity is the product of the regression rate r, shown in Fig. 1, with the density of black powder, $\rho_p = 1.75\ \mathrm{g/cm^3}$. If μ denotes the surface area of the collection of pellets per unit chamber volume, then a mass balance gives

$$\frac{d}{dt}\left(\rho_2 V_2\right) = m\mu\left(V_2/\epsilon\right) , \tag{9}$$

in which the final factor is the chamber volume occupied by flame at any given time.

Define a nondimensional pressure as $\varphi = p/p_0$ and a nondimensional time as

$$\tau = t\, m_0\, u\, R^\circ T_2 / \left(\epsilon\, p_0\, \overline{W}_2\right) \quad , \qquad (10)$$

where m_0 is the value of m at $p = p_0$. Put $m = m_0 f(\varphi)$, where the function $f(\varphi)$ can be obtained from Fig. 1. Equations (6) through (9) may then be used to show that

$$\frac{d}{d\tau}\left[\varphi\left(1 - \varphi^{-1/\gamma}\right)\right] = \left(1 - \varphi^{-1/\gamma}\right) f(\varphi) \quad . \qquad (11)$$

The integral of Eq. (11) gives the pressure-time history,

$$\tau = \int_1^{\varphi}\left[1 - \left(\frac{\gamma - 1}{\gamma}\right)\varphi^{-1/\gamma}\right]\left[\left(1 - \varphi^{-1/\gamma}\right) f(\varphi)\right]^{-1} d\varphi \quad . \qquad (12)$$

The spread rate dx/dt can be obtained from the relationship

$$\xi = x/L = V_2/\epsilon V \quad . \qquad (13)$$

From Eqs. (6) and (7) it seen that in Eq. (13)

$$\xi = 1 - \varphi^{-1/\gamma} \quad . \qquad (14)$$

A nondimensional rate of spread then is found from Eq. (11) to be

$$\frac{d\xi}{d\tau} = \xi(1 - \xi)^{\gamma+1} f/[1 + (\gamma - 1)\xi] \quad . \qquad (15)$$

A schematic illustration of the dependence of spread rate on flame position, as predicted by Eq. (15), is shown in Fig. 13. Also shown there is a curve for the nondimensional chamber pressure.

A number of aspects of this theoretical result on spread rate are worth comment. First, it is seen that theoretically the rate begins at zero, because the initial volume of burning pellets is zero. Of course, this is unrealistic because initially there will be a finite volume of burnt gas, produced by the initiator if not by the black powder. Moreover, the assumption that the hot salts move with the gas is unlikely to be realistic at the instant of initiation. A portion of the curve near $\xi = 0$ therefore should be excluded in Fig. 13.

Shortly thereafter, the model predicts a linear increase in velocity with position. This is caused by the continuously increasing volume of burning powder, under conditions such that the normal regression rate remains approximately constant; it is a direct effect of hot-gas motion. During this early-time perod, the distance-time formula is simply

$$\xi = e^{\tau} - 1 \quad , \qquad (16)$$

which has a linear growth for small τ and an exponential growth for large τ. This formula is likely to be in reasonable qualitative agreement with true distance-time relationships for the flame front in the primer charge.

Later, if the effect of f exceeds that of $(1 - \xi)^{\gamma+1}$, the velocity increases more rapidly than linearly with ξ, i.e. the flame travel is greater than that given by Eq. (16), because of the increase in normal regression rate with increasing pressure. This result (from Fig. 1) causes f to increase with ξ, thereby tending to produce increased acceleration. This effect is likely to be present in real charges as well as in this simplified model. A rough way of extending Eq. (16) to account approximately for this effect is to write

$$\xi = e^{f\tau} - 1 \quad , \qquad (17)$$

although in reality $\int_0^{\tau} f \, d\tau$ should appear instead of $f\tau$, when $(1-\xi)^{\gamma+1}$ is neglected.

As the flame approaches the end of the charge, the gasdynamic model predicts that the spread rate begins to decrease; eventually the rate is predicted to go to zero and the pressure to infinity. This effect is physically incorrect and is caused by breakdown of a number of assumptions of the model at late times. First of all, the assumption of constant T_2 becomes invalid. Secondly, the model has assumed that pellets occupy the entire chamber, but in reality there is additional free gas volume available in the main propelling charge. An improvement in the model can be effected by artificially increasing L to account for this excess volume and by employing the gasdynamic results only up to a value of ξ less than unity, say ξ_f. In this case ξ_f will be the ratio of the free volume in the primer to the total free volume of the propelling charge, i.e. it is seldom as large as 0.3. The model then, in general, probably should be used only for $\xi \lesssim 0.3$.

Although the model is one-dimensional as stated, there is no difficulty in applying it to charges of arbitrary shape. In the general case, ξ is the ratio of the free volume subtended by the spreading flame to the total free volume of the charge. Instead of giving a velocity or linear spread rate, the model then gives a rate of increase of volume, without determining the shape of the burning volume.

Perhaps the most important result of the model is its qualitative prediction of the dependence of primer delay time on design parameters. This prediction is given by Eq. (10). The nondimensionalization is such that τ is of order unity. Therefore, according to Eq. (10), the delay time varies as

$$t \sim (\epsilon\, p_0\, \overline{W}_2)/(m_0\, \mu\, R^{\circ}\, T_2) \quad . \tag{18}$$

To reduce the delay time one may decrease the void fraction, increas the surface to volume ratio of the black powder (e.g., use smaller pellets), increase the flame temperature, decrease the mean molecular weight of reaction products, or increase the ratio of the normal regression rate to the pressure. Most of these predicted dependences are physically reasonable over a fairly wide range of conditions. For example, the dependence on pellet size is qualitatively in agreement with the observations in Ref. 60.

The model could best be tested by measuring spread rates in primer charges.

3.4 A Random Walk with Multiplication for Flame Spread through Black Powder

The worry in the gasdynamic model is that the hot particles may not follow the gas motion. The opposite extreme is that in which each hot particle travels with a fixed constant velocity, say of magnitude v, independent of the gas motion. Since experimental observations suggest that the particle velocity is not related to the gas velocity, it would seem reasonable to assign each hot particle a constant velocity, provided that the gas pressure is not too high, the particle is not too small, and the distance the hot particle travels is not too great (i.e., the packing is not too loose). This velocity might be produced either by the rapid burst of combustion-produced gas at the surface of the pellet when the particle is generated or by continued gas production in the wake through continuing combustion of the particle as it travels. Of course, there will be a distribution of velocities among hot particles, but for the purposes of discussion the distribution can be approximated as a delta function.

The particle velocity v will not be identical with the flame spread rate because the hot particles are obstructed in their travel by the black powder pellets. One might assume that the particles are emitted in random directions and that they travel an average distance δ before encountering another pellet. The value of δ will depend on the pellet size and the degree of packing. It would appear that δ is likely to increase with increasing pellet size, probably proportionally, but that δ will be appreciably smaller than the size of a typical pellet.

Given v and δ, and given that hot particles travel in random directions, there exists a basis for a spread model based on a three-dimensional random walk. Particles may be viewed as moving in a straight line for a distance δ, stopping to select a new direction at random, and then again moving straight for a distance δ, etc. The random walk in three dimensions is well known,[65] but its visualization in the present problem is more difficult. It is usually assumed that the entire three-dimensional space is available to the particle. In the present case only the free volume is available; at each step approximately half of the 4π solid angle is excluded from the selection of direction by the presence of the black-powder pellet on which the particle is generated. It should be easy to devise geometrical arrangements in which this exclusion strongly influences the character of the random walk. However, it should also be possible to hypothesize sufficiently randomly oriented surfaces of black powder for the process to be viewed as an ordinary random walk occurring in the free volume only.

There are aspects of the ordinary random walk that are not consistent with the existing knowledge on flame spread. A Gaussian density function results, and the distance traveled by a particle is known to be proportional to the square root of time, $x \sim \sqrt{t}$. Thus, the effective macroscopic velocity of the particle decreases as time increases, $x/t \sim 1/\sqrt{t}$. This would suggest, contrary to experiment, that the spread rate is greatest at the time of initiation. The discrepancy implies that the conventional random walk is insufficient for describing the spread process.

To circumvent the difficulty, one might try to allow v to increase with pressure (i.e., with time), reasoning that it should increase with increasing normal regression rate. However, this approach does not seem very promising; for example, it is unlikely to produce agreement with the experiments of Blackwood and Bowden[14] at atmospheric pressure. A better approach is to recognize that after a hot particle ignites a point on the surface of a pellet, that point usually emits many, not one, hot particles, which travel in different randome directions (see, for example, Fig. 7). The model that suggests itself then is one of a random walk with multiplication. At each step, instead of one particle leaving the point in a random direction, a number $n > 1$ of particles leave the point in random directions. This type of multiplication will modify the dynamics of the random walk and physically could be expected to produce an effective macroscopic velocity that remains constant or increases with time.

The model is illustrated schematically in Fig. 14 for the case $n = 3$. The four parts, (a), (b), (c) and (d), show the travels that occur at four successive time steps. From the point at which the first particle impinged, three particles emerge in (b). From each of the three new impingement points, three more particles emerge in (c). It is seen that intensities of combustion would increase rapidly, as observed experimentally.

A three-dimensional random walk with multiplication apparently has not been analyzed in the literature. The mathematical problems involved would be quite interesting. The problem might well be tractable and might admit steady-state traveling-wave solutions corresponding to a constant rate of flame spread. The mathematical problem will not be attacked here because the present interest lies only in qualitative aspects of the results.

A characteristic diffusion coefficient for the model is $\alpha = v\delta$. A respresentative spread velocity then would be α/ℓ, where ℓ is a characteristic distance. Without further analysis, it is unclear what the appropriate identification of ℓ is. It might be expected that ℓ will exceed δ and also exceed the representative pellet size; perhaps ℓ would be of the order of the diameter or length of the charge. The spread rate $v\delta/\ell$ would then be appreciably less than v. If 5000 cm/sec is representative of v (Section 3.2) and 60 cm/sec is a characteristic spread rate,[14] then δ/ℓ would be of order 10^{-2}.

The delay time for the primer, predicted by the model, would be of order

$$t \sim L(\delta/\ell)/v \qquad (19)$$

where L is the length of the primer. If v is proportional to m and if δ is proportional to ϵ/μ then Eq. (19) agrees with Eq. (18) in at least two respects. There would clearly appear to be other respects in which the two equations differ. Further study of the random walk with multiplication would be of interest.

3.5 A Time-Sequence View of Flame Spread through Black Powder

In the combustion of pellets of black powder there are a number of elementary steps involved to which characteristic times can be ascribed. It has just been indicated that there is a travel time of hot salt particles from one pellet to another. In addition there is a characteristic ignition time for a point on the surface of a pellet at which a hot particle lands, and there is a characteristic time for combustion to spread from an ignition point on a pellet to the opposite side of the pellet. If these three times are denoted by t_t, t_i and t_s, respectively, then in a conventional view of combustion the total time required for the three steps sequentially is

$$t = t_t + t_i + t_s \quad . \tag{20}$$

The model illustrated in Fig. 15 might be adopted for flame spread through black powder, in which case the spread rate is

$$u = \ell/(t_t + t_i + t_s) \quad . \tag{21}$$

In this view, then, the spread rate is controlled by the slowest of the three sequential processes.

It is unclear under what conditions a sequential view such as this might be useful. The random walk of the preceding section effectively assumes that t_i is short compared with t_t and that although t_s is very long this third process need not occur, the three-dimensionality serving to circumvent the need for spread of combustion along the surface of the pellet. The assumption that t_i is negligibly short has been made almost universally for black powder in hot-salt ignition. If one realizes that the current estimates of v imply that $t_t = \delta/v$ lies between 10^{-5} and 10^{-4} sec typically, then the assumption that $t_i << t_t$ necessitates $t_i \leq 10^{-6}$ sec, which would correspond to an extremely fast ignition. Thus, there may be questions worth pursuing as to whether ignition indeed can always be assumed to be instantaneous. Unfortunately in the absence of more information on t_i, there appears to be no basis for making any other assumption.

When Eq. (21) is valid, it would seem that t_t and t_i both generally are small compared with t_s (see, for example, Figs. 6, 7 and 12 and the end of Section 3.2). Equation (21) therefore apparently can be simplified to $u = \ell/t_s \approx u_s$, the rate of spread of flame along the continuous surface of black powder. Spread rates along continuous surfaces often are comparable with linear regression rates. Typically they are somewhat larger, but seldom are they an order of magnitude larger for fuels such as black powder that do not easily tend to produce combustible gaseous vapors. Thus, roughly $u_s \approx r$, and under these conditions the spread rate should be roughly comparable with the normal regression rate. The model therefore may be valid for very fine powder (maximum diameter less than 100μ). Study of this type of spread might contribute to understanding of normal regression mechanisms.

The time-sequence view does not appear to be particularly useful for spread through typical primer charges. If black-powder initiation is achieved, then spread through the primer is more likely to be described by a model in one of the two preceding sections, and ignition of the main propellant by hot salts from the black powder is likely to be rapid where close communication between the primer and the propellant occurs.

4. A LABORATORY TEST

4.1 Background

In the previous section it has been reasoned that the critical function of black powder in the propellant train is to spread the flame over the length of the M1 propellant. This flame spread occurs essentially at constant volume and serves the function of rapidly providing numerous ignition points of the main propellant, distributed along the centerline region of the cartridge. The rapid distribution of ignition points increases the quickness of the charge and results in higher force being applied to the projectile early in its travel, at times of optimum effectiveness. The black powder accomplishes this rapid spread without developing strong spatial nonhomogeneities in pressure, characteristic of (entirely unacceptable) detonative processes.

According to this view, as developed in Section 3, the key element that black powder contributes is a rapid particle-to-particle propagation of the flame throughout the bed of the primer. The initiator is presumed to be always sufficiently energetic to ignite the black-powder primer at the breech end. Reaction products of black powder are sufficiently hot, voluminous and penetrating to ignite M1 readily where spread through the primer has occurred. The black-powder particles themselves burn considerably more slowly and contribute measurably but not too importantly to the late-time evolution of gas and heat. It is recognized that black powder performs functions other than spreading the flame in propelling charges, but it is hypothesized that spread is its principal function, the main one that should be investigated in laboratory acceptance tests.

4.2 Test Concept

The test is designed to provide spread-rate data under conditions that simulate actual operating conditions of the igniter (see Fig. 16). A constant-volume bomb is selected because it models closely the environment of the propellant during flame spread. A standard primer tube and liner are employed to contain the black powder. The tube is fully loaded with powder, in the manner normally encountered in cartridges, and the remainder of the bomb is filled with glass propellant-simulators. At each of the eleven axially spaced holes along the tube, ionization gauges are installed to record the moment of flame arrival. The tube is provided with a standard M61 initiator to best simulate real-world initiation conditions. In addition, the bomb is fitted with a pressure gauge for obtaining quickness and force.

The key measurement to be made is the rate of flame spread. Ionization gauges are simple and reliable devices that record the presence of flame. A diagram of a simple gauge and its position and associated instrumentation is shown in Fig. 17. Placement of the gauges outside the perforations of the primer tube serves to better monitor the function of the black powder in igniting the propellant; spread through the black powder itself is not as important as emergence of the flame at the perforations. The coaxial outer electrode of the gauge is grounded and the voltage difference between that and the inner electrode is recorded on an oscilloscope. In gaseous flames, voltages on the order of 3 mv are produced; because of the hot salt products of combustion, the voltages may be considerably higher for black powder. With eleven gauges, eleven traces would have to be displayed on the oscilloscope if the illustrated technique is employed. Alternatives are to use fewer gauges (four should be sufficient for providing the needed flame-spread history) or to design a simple electronic timing device that records the onset time of each signal without obtaining its subsequent time history.

The test procedure is simply to record the initiation time, the flame arrival times at each of the ionization gauges, and the pressure-time history. These values are to be compared with values previously measured for a standard batch of black powder, using the same apparatus and test procedure. Too great a disagreement in any of the time intervals for flame arrival, or in quickness or force, should be cause for rejection of a new propellant lot. Conversely, sufficiently close agreement between data for the standard batch and the new lot justifies acceptance, since it demonstrates closely comparable flame-spread properties for the two lots.

There are numerous variants of the proposed procedure that could be acceptable. Any such variation would move in the direction of a less complete simulation of the end use, but also in the direction of less expensive testing. A tradeoff has to be established between expense and the degree of simulation. Trials would be needed to establish where the optimum tradeoff lies.

A simple variant is to forego use of the propellant simulation in the chamber. This will increase the free volume, slow the spread and reduce the peak pressure. However, even so, it is possible that through such a test, comparison with a standard black powder would reveal whether a new batch possesses acceptable performance.

Another variant is to replace the M61 percussion initiator with two electric matches. Electric matches are well-developed, simple and reasonably reliable devices that ignite black powder fairly well.[57] Their use could provide considerable simplification over percussion initiation, and since the black powder apparently primarily requires heat for initiation, it should make little difference whether that heat is provided by a standard initiator or by an electric match.

Another variant would be to reduce the number of ionization gauges to one. This single gauge may be placed at the last perforation of the primer tube, farthest from the initiator. Use of a single gauge involves the assumption that the time for the flame to reach the end of the primer will be the same in two tests only if the entire history of flame spread is the same in each test. Variations in conditions might well be such that this is a reasonable assumption. However, ignition delays associated with the initiator may be such that if this general approach is adopted, it would be best to use two gauges, one at the first perforation to establish a zero time.

Finally, consideration might be given to a much less expensive test that does not involve use of a bomb at all. This is the atmospheric-pressure flame-spread test of Blackwood and Bowden.[14] The black powder is filled in an open slit, say 5mm wide, 3mm deep and 10 cm long and ignited centrally by a hot wire. The spread rate of the flame is then recorded. Blackwood and Bowden made this measurement with streak photography. Although streak photography is not very expensive and provides a considerable amount of information, an even simpler approach would be to employ one or two ionization gauges placed in the black powder. Acceptance would then be based on tolerable agreement between the measured time interval between initiation and flame arrival. Disadvantages of this approach are that it does not test the doner-receiver relationships between the black powder, its initiator, and the main propellant at all, and that pressure-time histories are not simulated at all. However, if the major function of black powder that could produce difficulties is flame spread, and if disagreement in spread rates at elevated pressures is reflected in disagreement at atmospheric pressure, then the test is a successful screening procedure.

One might consider making use of the reasonable hypotheses that spread is produced by hot particles leaving the surface of the burning powder and that these particles have characteristics determined entirely by the particle size distributions of the constituents that make up the black-powder pellet. For example, the fine mix of a jet mill may give rise to finer hot salt particles, in comparison with the coarser mix of a wheel mill, and these finer particles may be less penetrating, thereby spreading flame more slowly. This hypothesis leads to the conclusion that spread properties can be tested without performing combustion experiments. It is only necessary to measure the size distributions of particles that form the final product, especially potassium nitrate, since this is probably the principal traveler in spread. If the size distribution is in tolerable agreement with the standard, then the product can be accepted. In fact, a size distribution or mean size easily can be written into specifications. An approach of this kind is not recommended here. It is felt that our knowledge of flame-spread mechanisms of black powder is too primitive to justify use of a test that does not involve combustion. A size-distribution requirement would appear to be too stringent an imposition on new manufacturing processes, and it might prevent small modifications in black powder that could be beneficial from the viewpoint of performance.

5. CONCLUSIONS

1. Although scientific study of black powder has been pursued since the renaissance, its combustion mechanisms are so complex that incomplete, mainly qualitative knowledge of its behavior is available today.

2. A detailed model for normal regression of burning black powder has been developed recently in the Soviet Union, but the model does not seem to produce agreement with the experimentally measured regression rate.

3. From existing studies, notably that of Blackwood and Bowden, it seems likely that the role of black powder in propelling charges is to spread flame quickly to multiple ignition points of the main propellant.

4. A small amount of information is available in the literature on flame-spread properties of black powder, and rough estimates of spread rates can be made.

5. High-speed framing photography of laser-ignited, spark-ignited and hot-wire ignited black powder reveals additional details of the burning mechanism and provides estimates of velocities of motion of hot salt particles, emitted from the surface of the burning powder, which are likely to be responsible for rapid flame spread.

6. The high-speed photography tends to show relatively slow spread of flame along the continuous surface of a black powder particle.

7. Scanning electron micrographs of quenched particles show directly the existence of a melt layer on the surface of black powder during combustion, as expected.

8. A gasdynamic model predicts the rate of flame spread through a black-powder charge and also the dependence of the delay time on experimental parameters; although limiting cases in which the model may be correct are identified, it is not known whether the model may be valid under practical conditions.

9. From existing experimental information on flame spread, it would appear that a random walk with multiplication may properly describe spread that occurs through travel of hot salt particles.

10. Characteristic times for hot-particle travel, ignition by impingement of hot salts and flame spread along a continuous black-powder surface

are poorly known and are in need of better experimental definition.

11. It is possible to construct a closed-bomb apparatus in which the flame-spread role of black powder can be tested for product acceptance in a use-related manner.

12. Ionisation gauges appear to be easy to employ in testing flame-spread properties of black powder.

13. Inexpensive tests of flame spread through black powder can be made at atmospheric pressure.

6. RECOMMENDATIONS

1. A closed-bomb apparatus, described herein, should be constructed for the purpose of assurance of proper performance of black powder in propelling trains.

2. The utility of atmospheric-pressure flame-spread measurements for assuring performance of black powder should be investigated.

3. Experimental research should be pursued on flame spread through black powder, with special emphasis on ignition times associated with impingement of hot salts, on rates of flame spread along continuous surfaces of black powder and on motions of hot salt particles generated in the surface burning.

4. Predictions of the gasdynamic model, given herein, for flame spread through a black-powder charge should be tested experimentally.

5. The mathematics of the random walk with multiplication, for modeling flame spread through black powder, as described herein, should be investigated.

6. Further theoretical study of the normal regression of a burning surface of black powder should be pursued with the objective of ascertaining the reasons for the shortcomings of the model recently developed in the Soviet Union.

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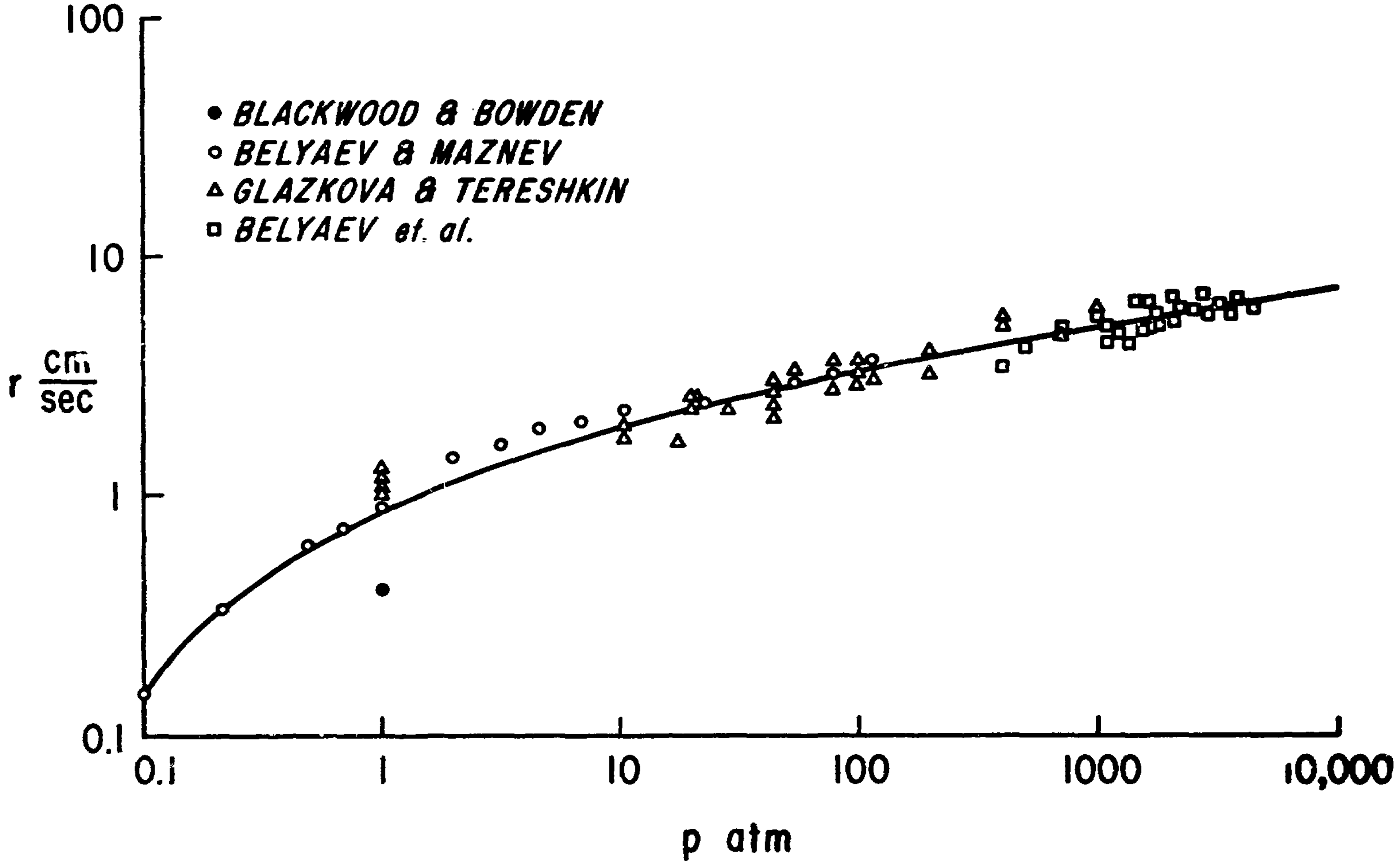

Fig 1 The normal regression rate of black powder as a function of pressure

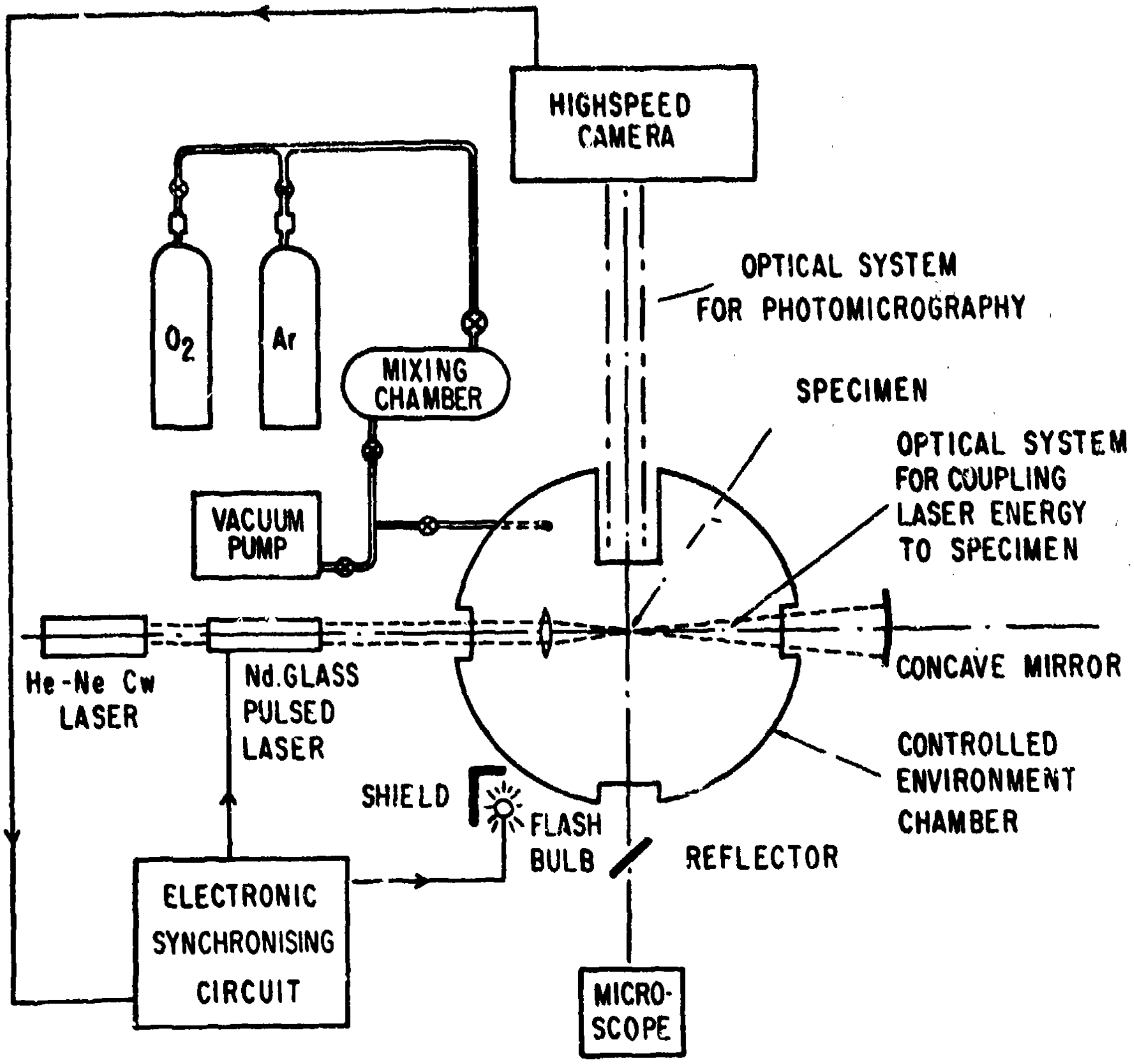

Fig 2 Schematic diagram of combustion experiment employing laser ignition

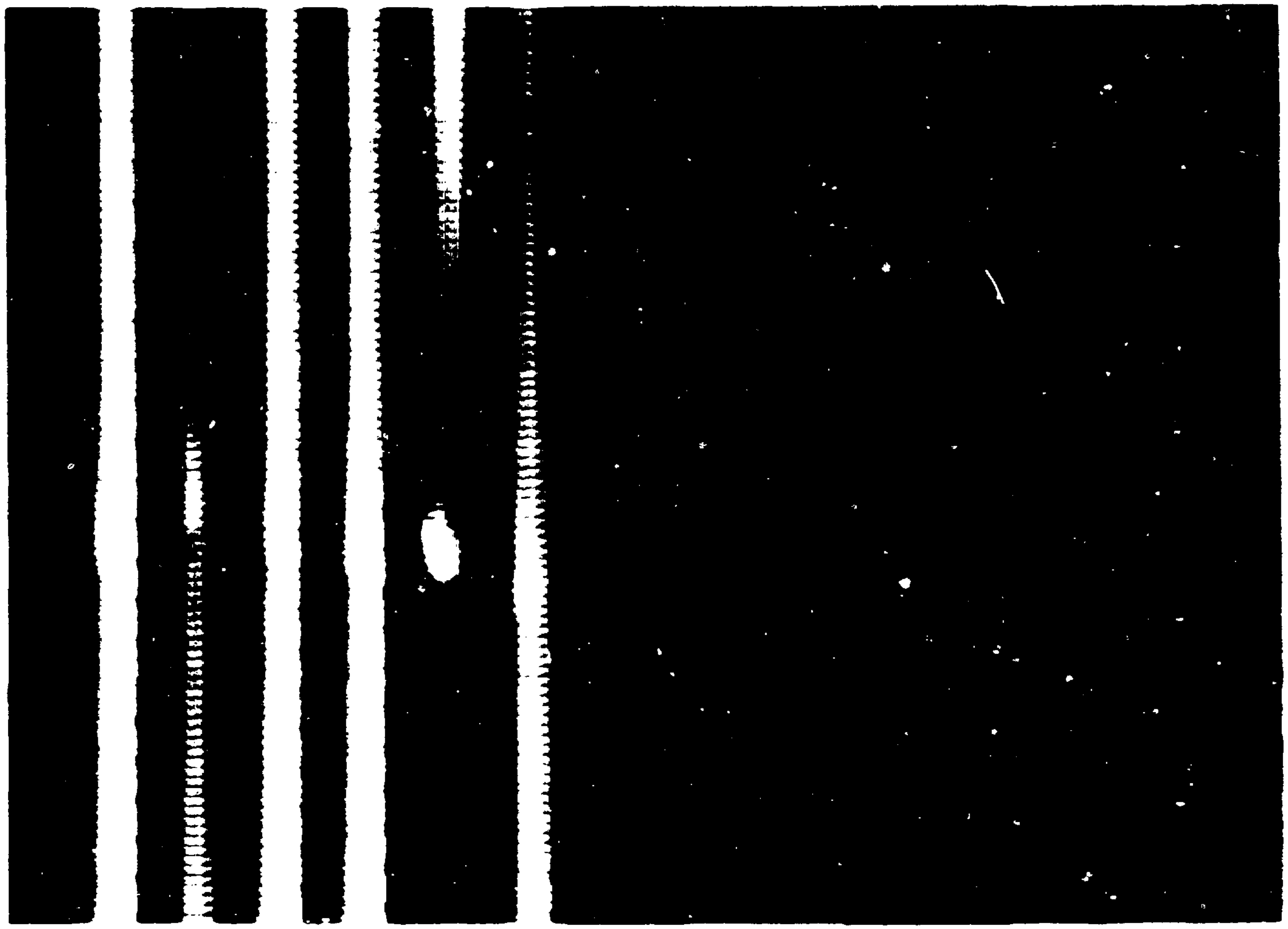

Fig 3 Ten sequences of laser firings. Left to right: glass probe only; glass probe only; carbon particle 5 x 5 x 4; carbon particle 5 x 5 x 4; black powder 1 x 2 x 2.5; black powder 20 x 10 x 15; black powder 2 x 3 x 2; magnesium, 5 particles in the range 0.2 to 2; black powder 4 x 6 x 4; black powder 4 x 4 x 3.5 (dimensions in hundreds of microns)

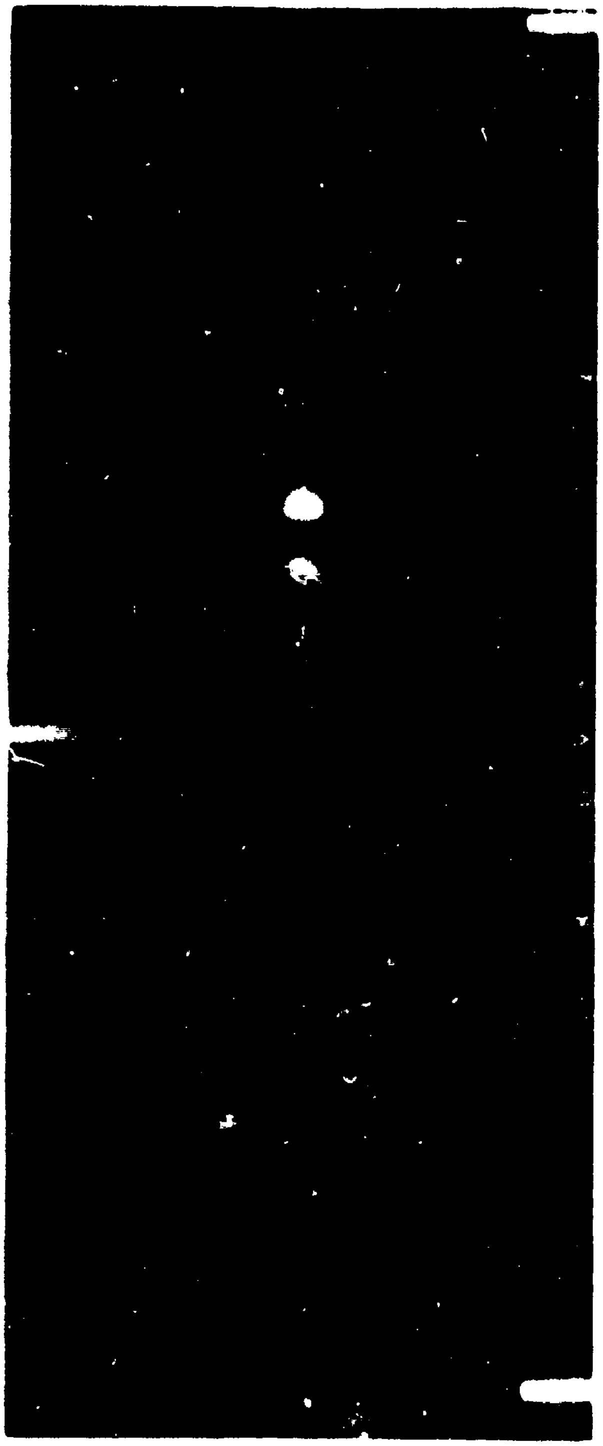

Fig 4 A magnified strip for a particle of smokeless powder, 5 x 5 x 2.5

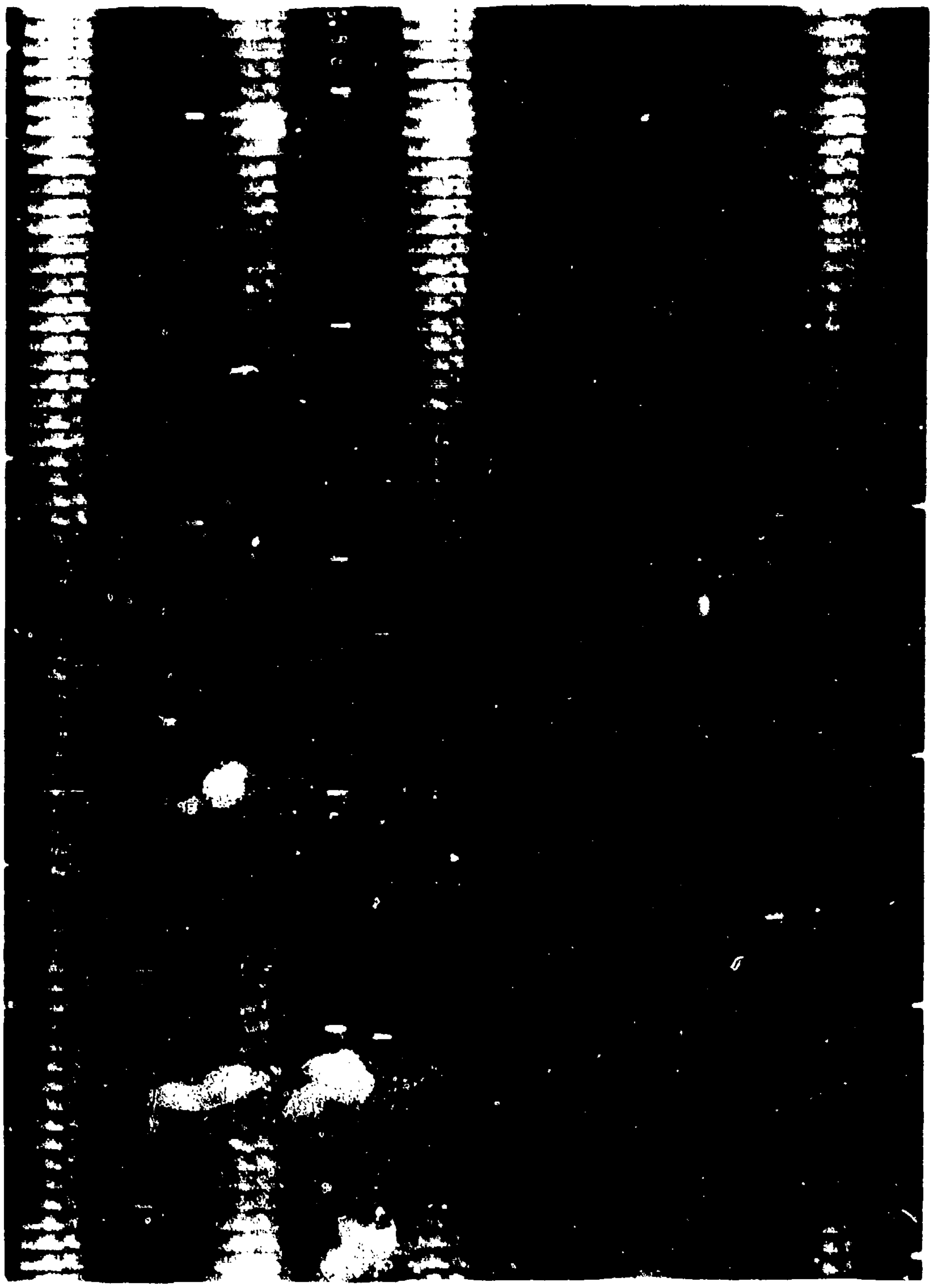

Fig 5 Five sequences for particles of smokeless powder, 5 x 5 x 2.5

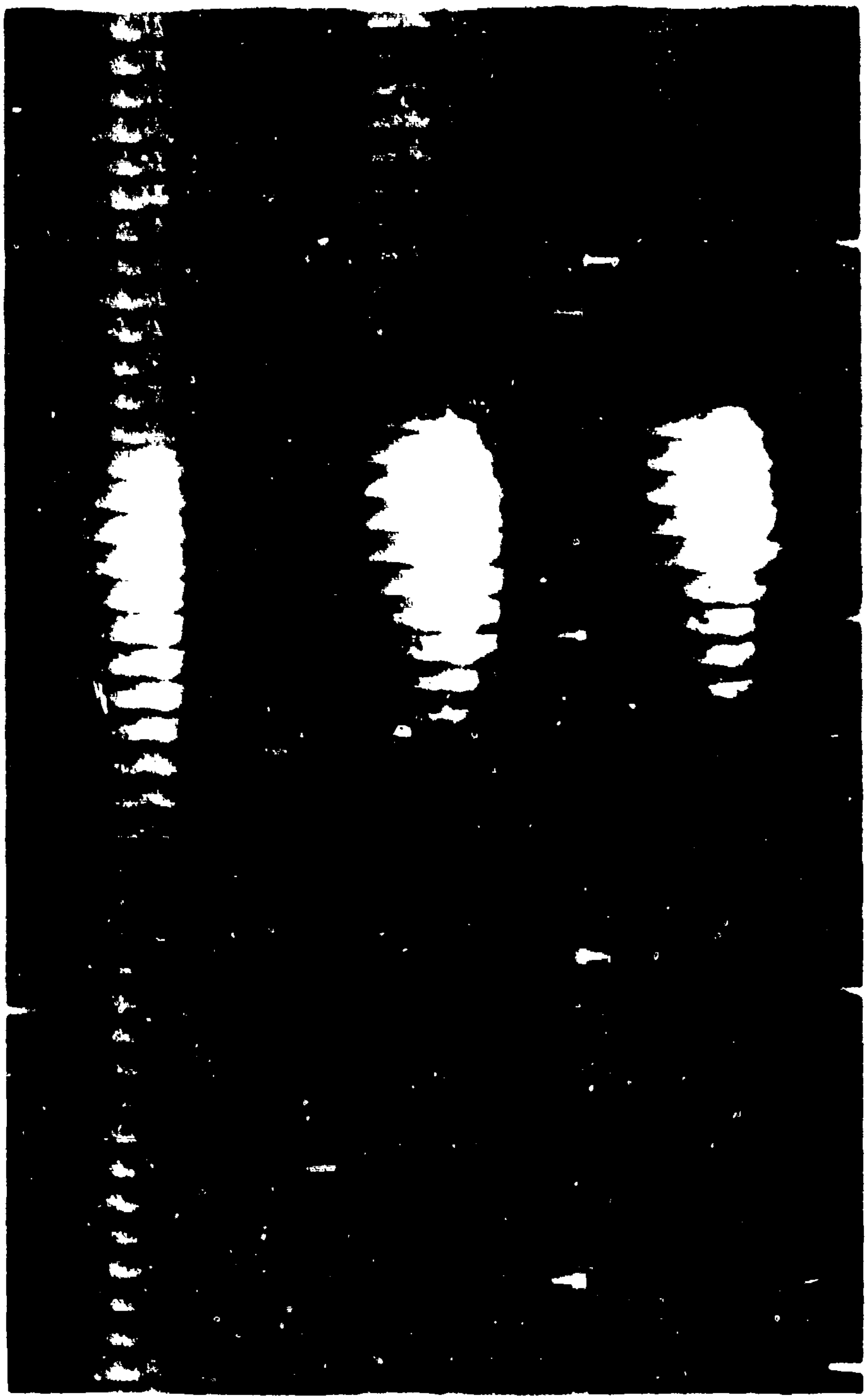

Fig 6 Three backlighted sequences for black powder. Particle sizes, left to right: 3 x 3 x 1.1, 8 x 8 x 5.5, 8 x 8 x 6

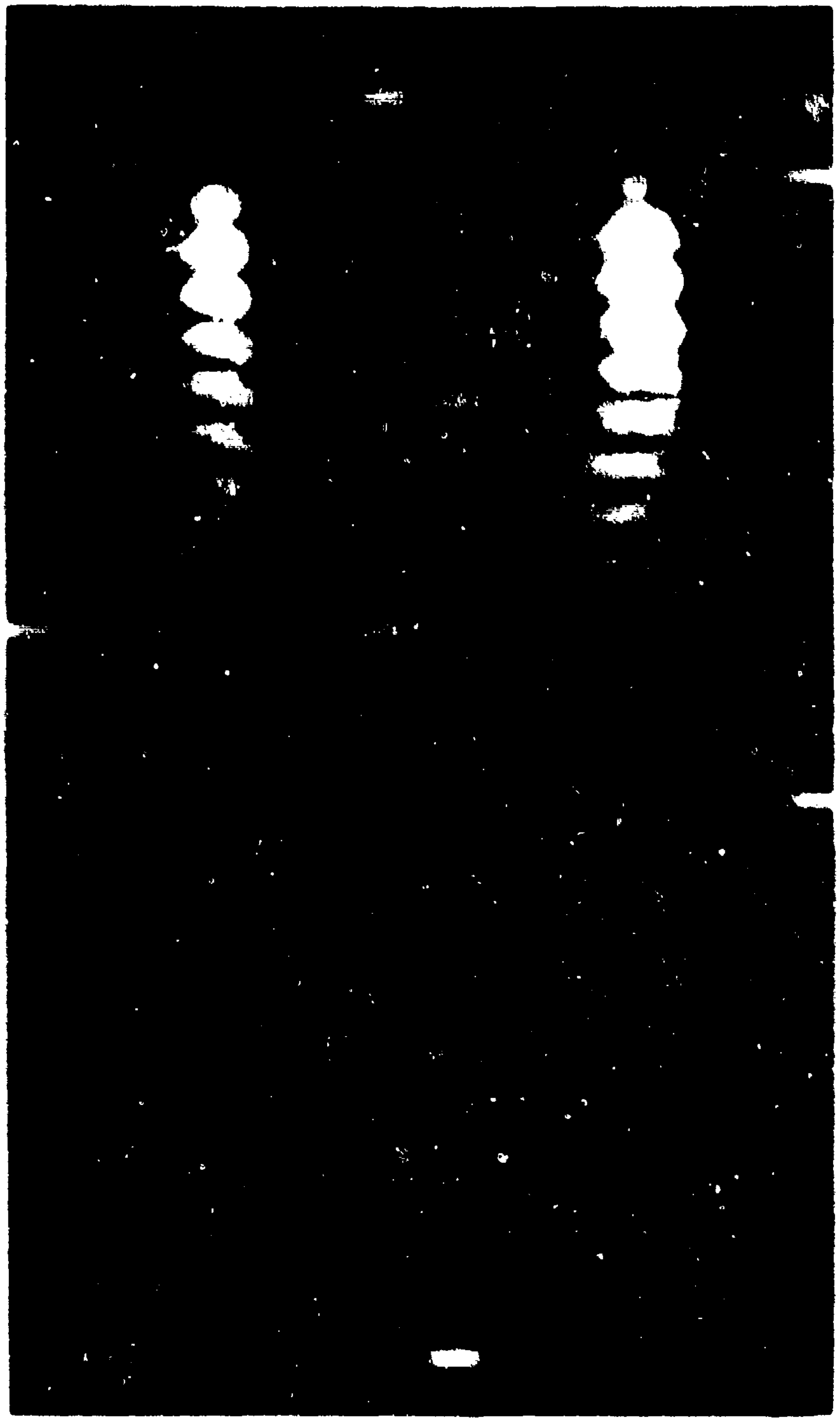

Fig 7 Two non-backlighted sequences for black powder. Particle sizes, left to right: 3 x 3.5 x 1, 6 x 6 x 1.2

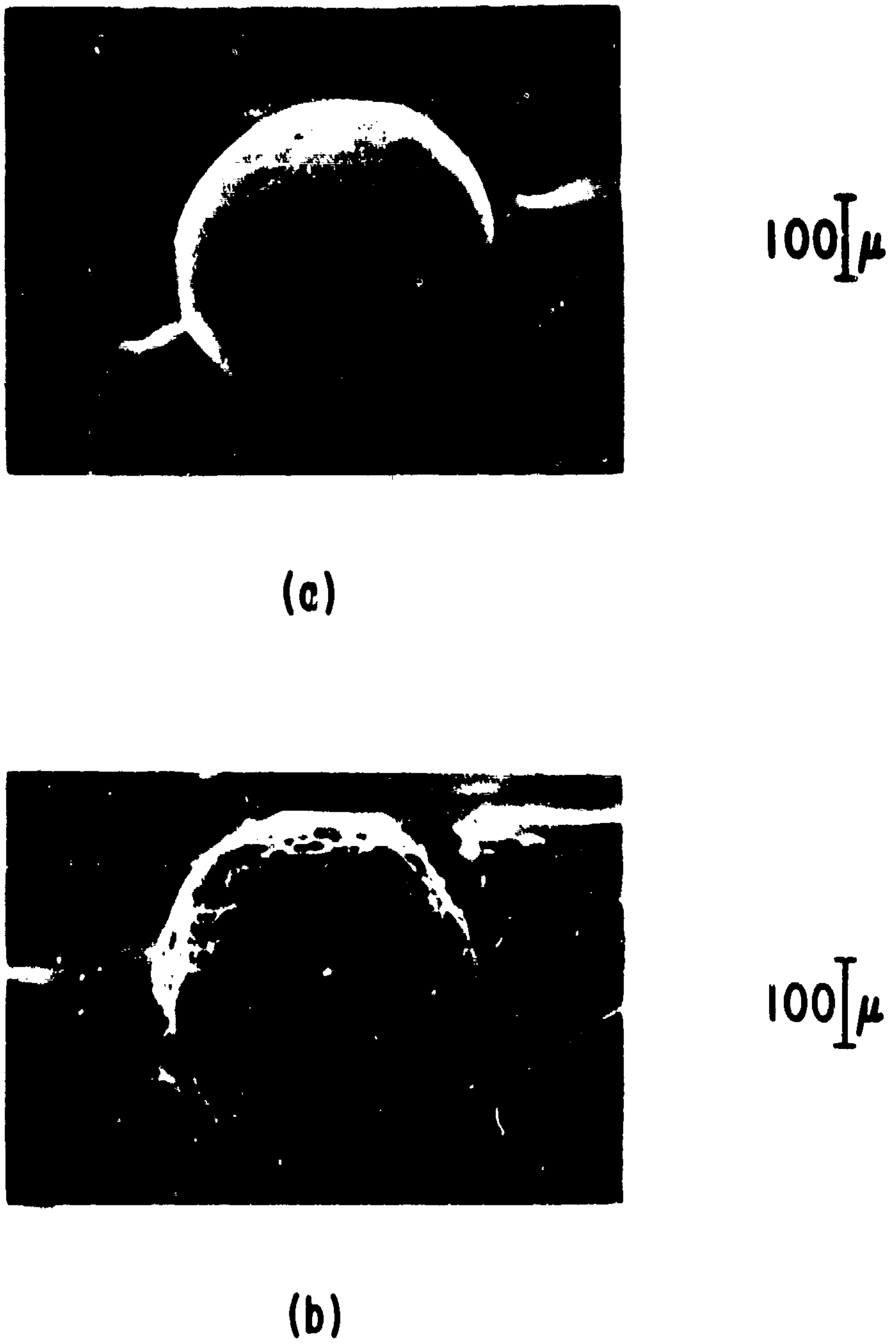

Fig 8 Scanning electron micrographs of smokeless powder before and after laser irradiation

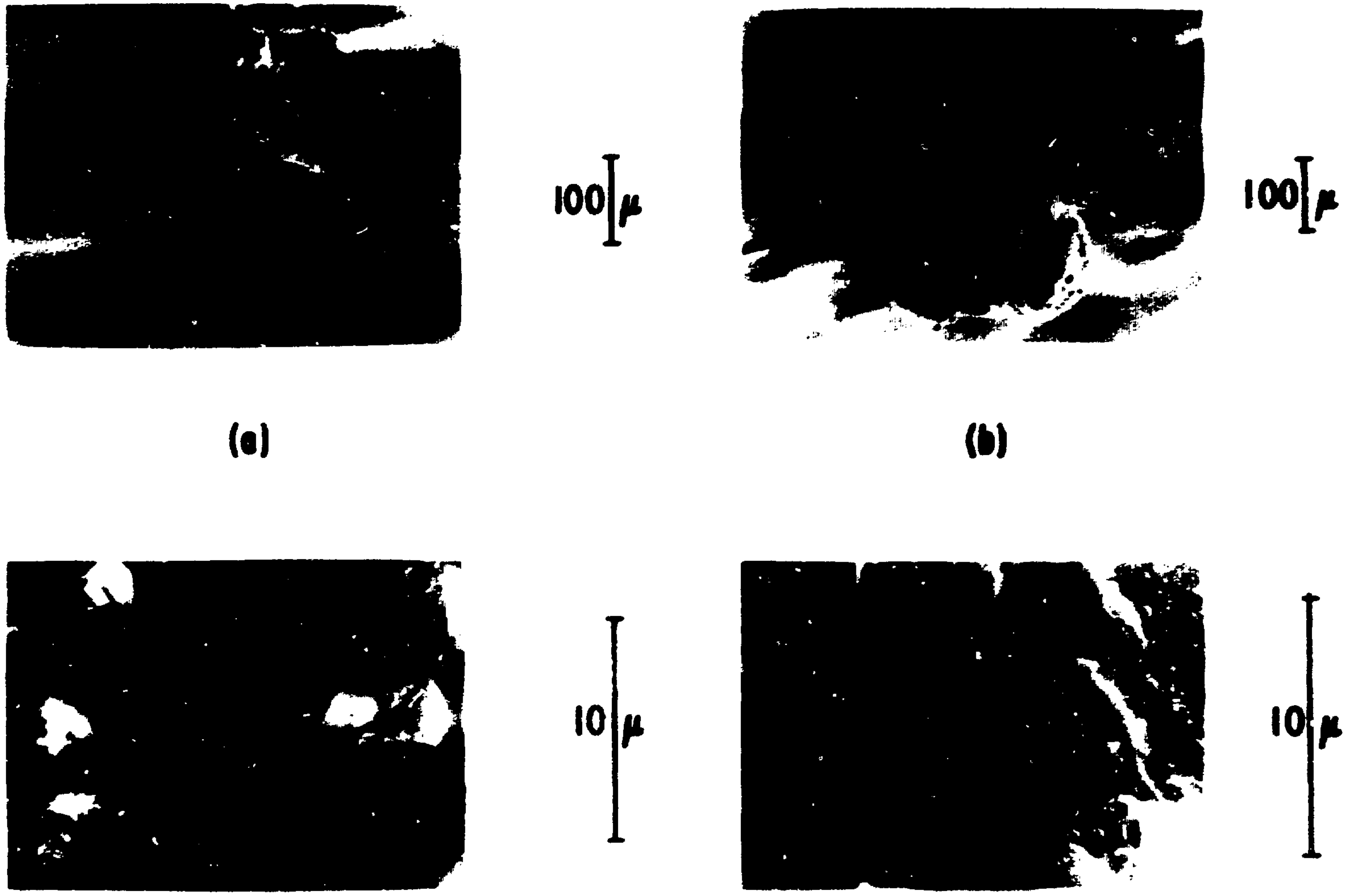

Fig 9 Scanning electron micrographs of black powder before and after laser irradiation

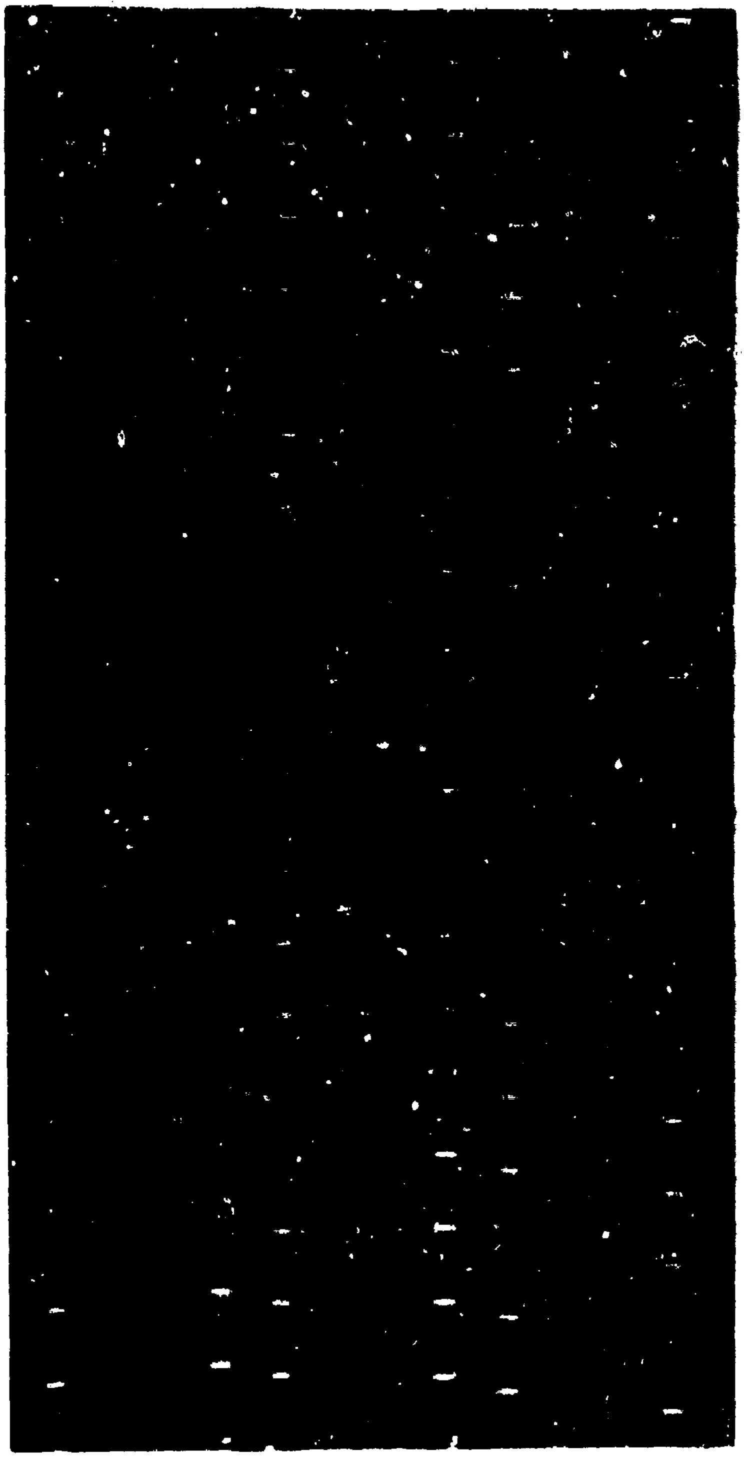

Fig 10 Three sequences of spark ignition for black powder (mag. 0.3)

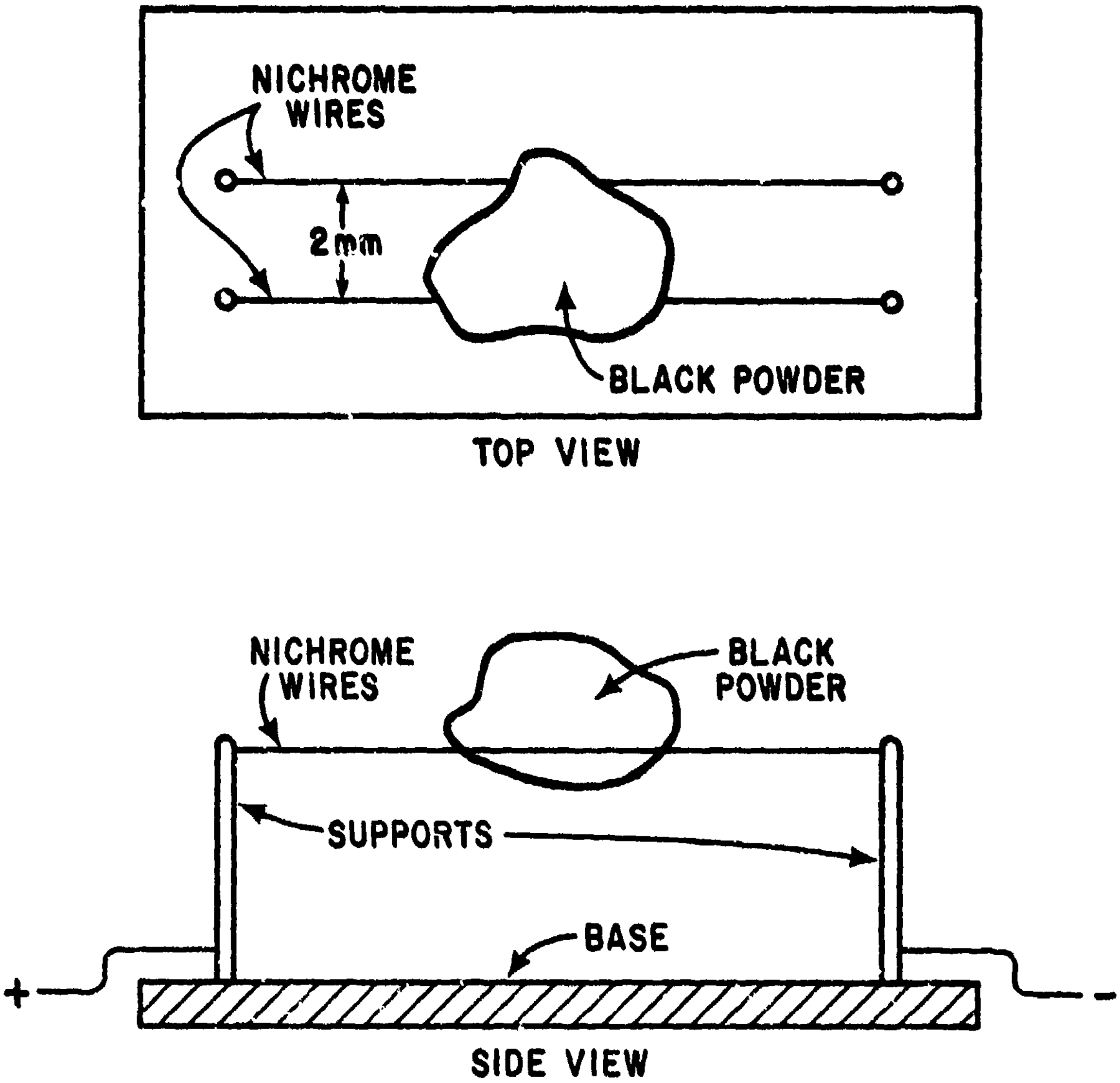

Fig 11 Schematic diagram of support arrangement for hot-wire ignition of black powder

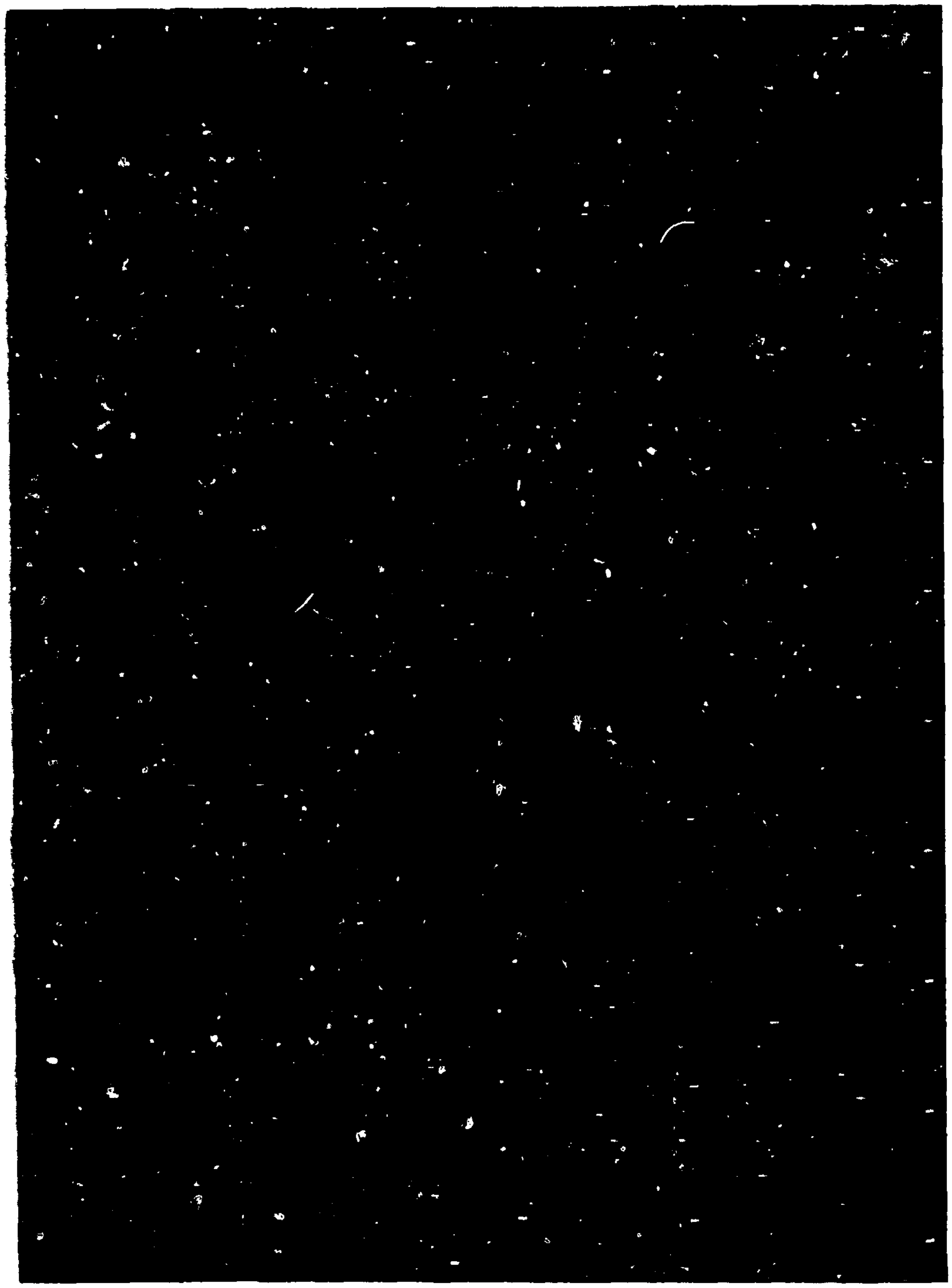

Fig 12 Non-backlighted sequence of hot-wire ignition for black powder (mag. 0.2)

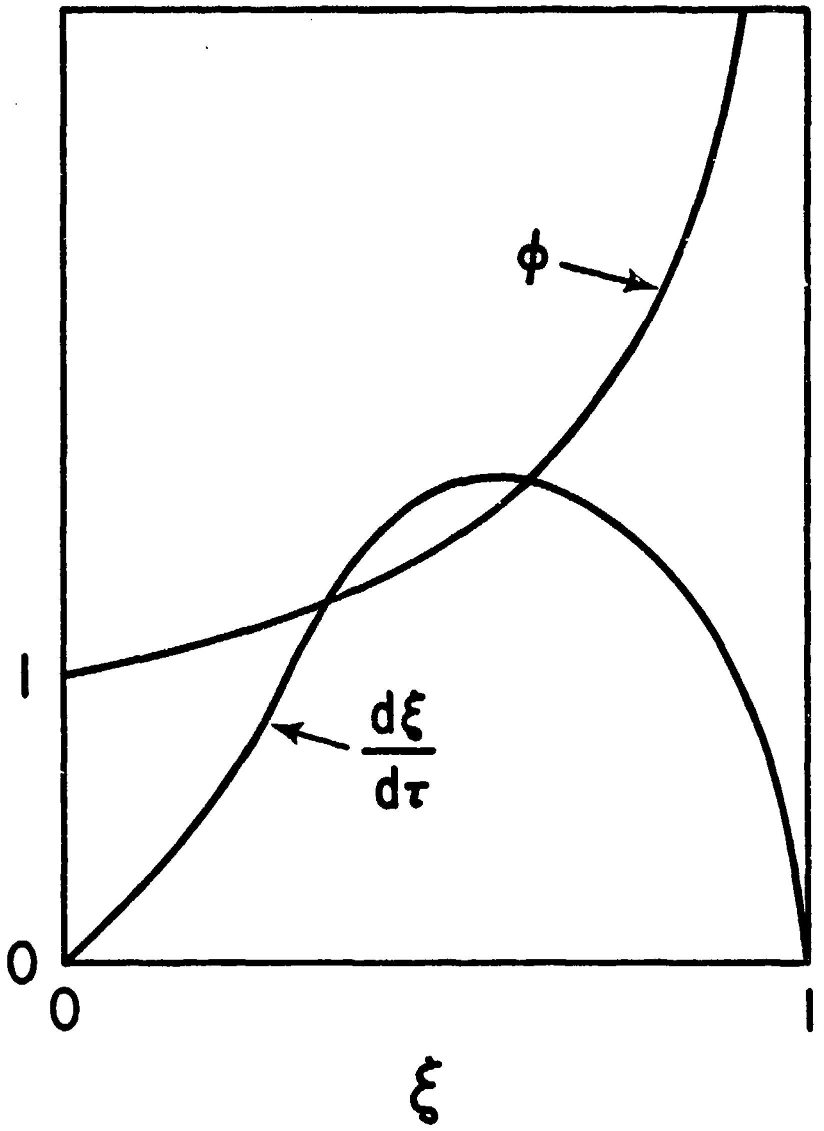

Fig 13 Schematic illustration of spread rate and pressure as functions of distance from the point of ignition for the gasdynamic model

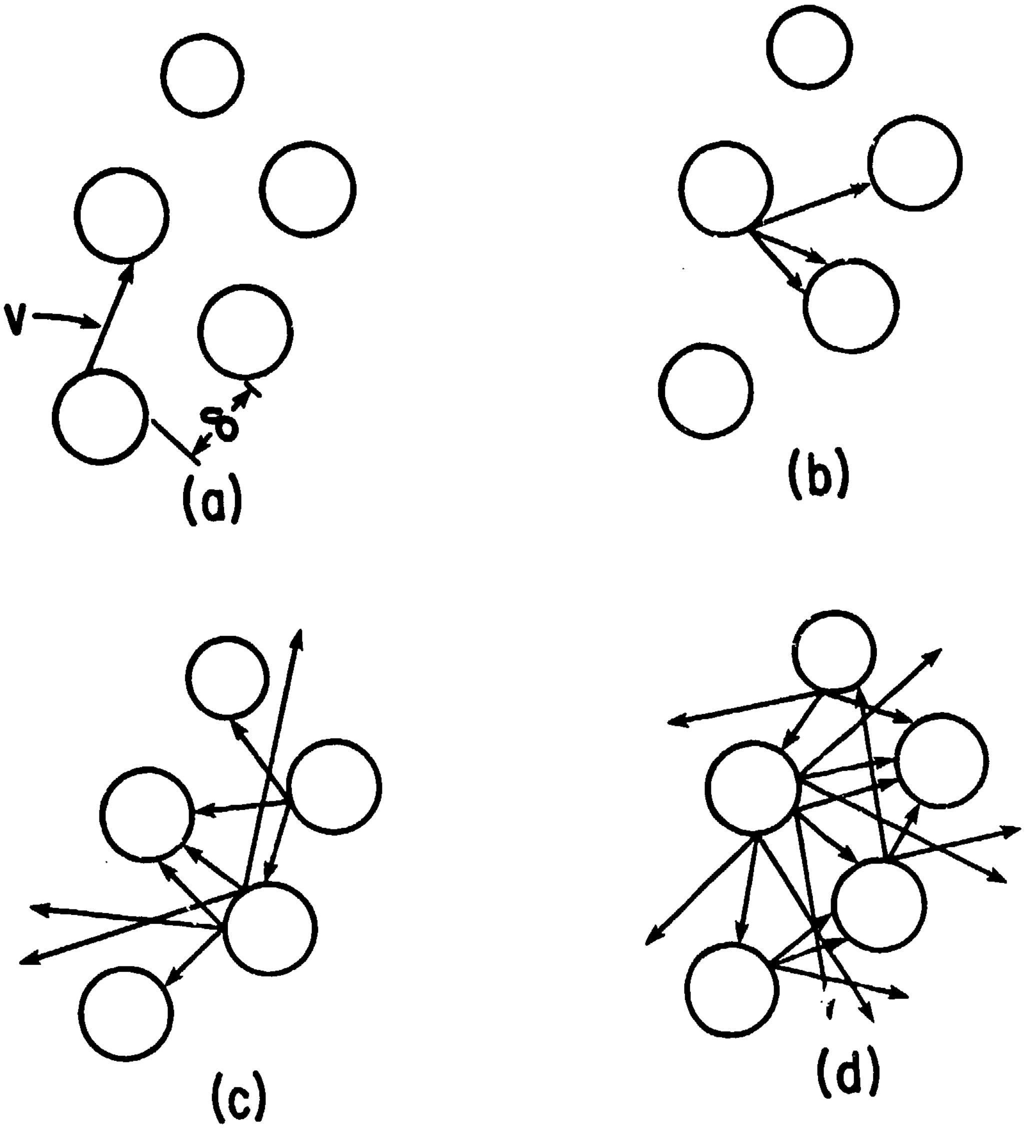

Fig 14 Schematic model of random walk with multiplication

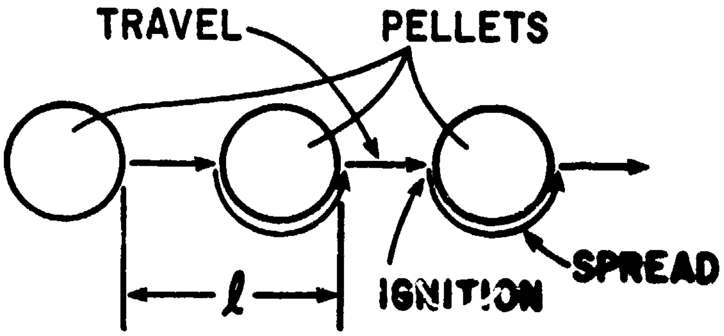

Fig 15 Schematic model of time-sequence spread

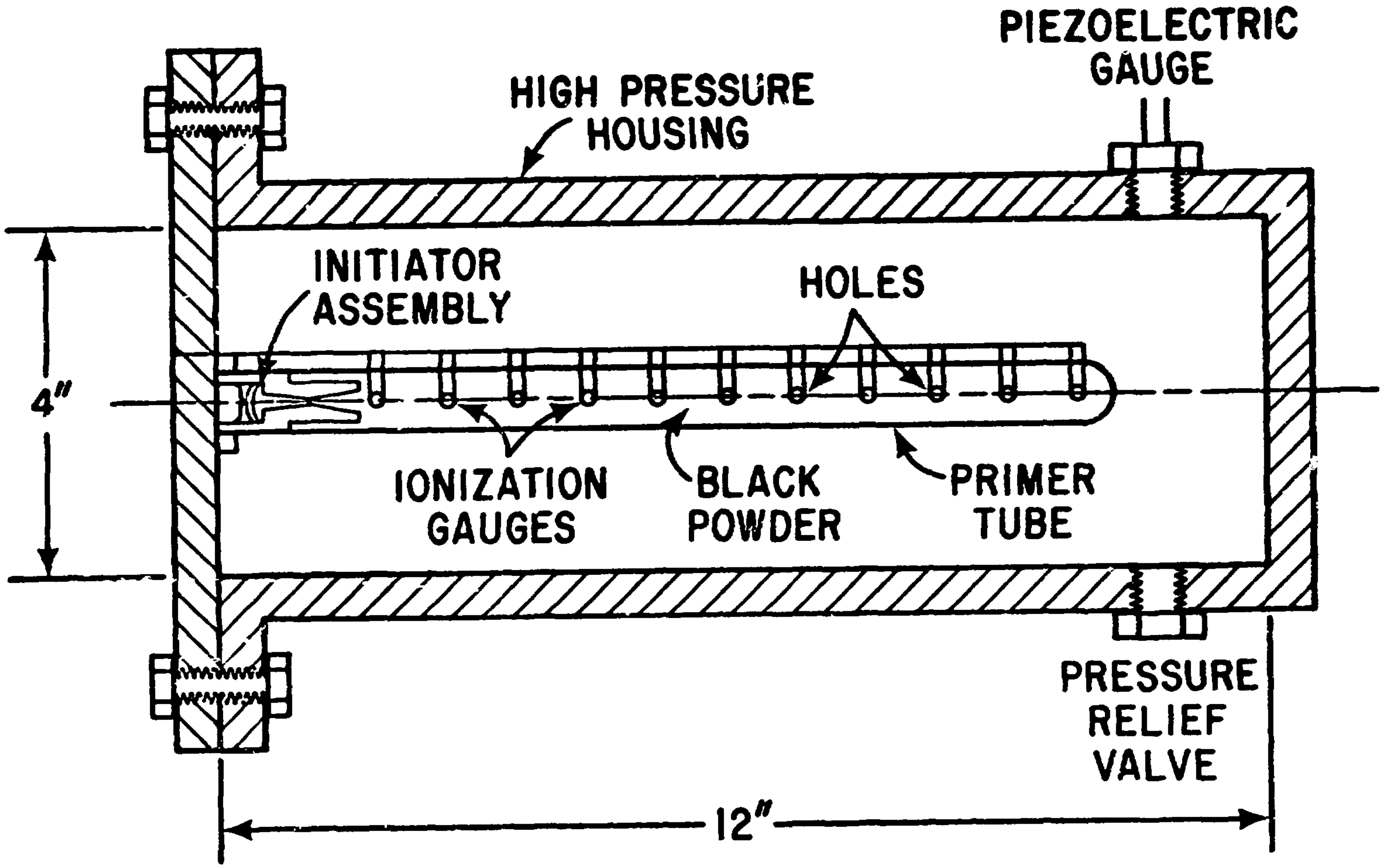

Fig 16 Schematic of bomb assembly for spread test

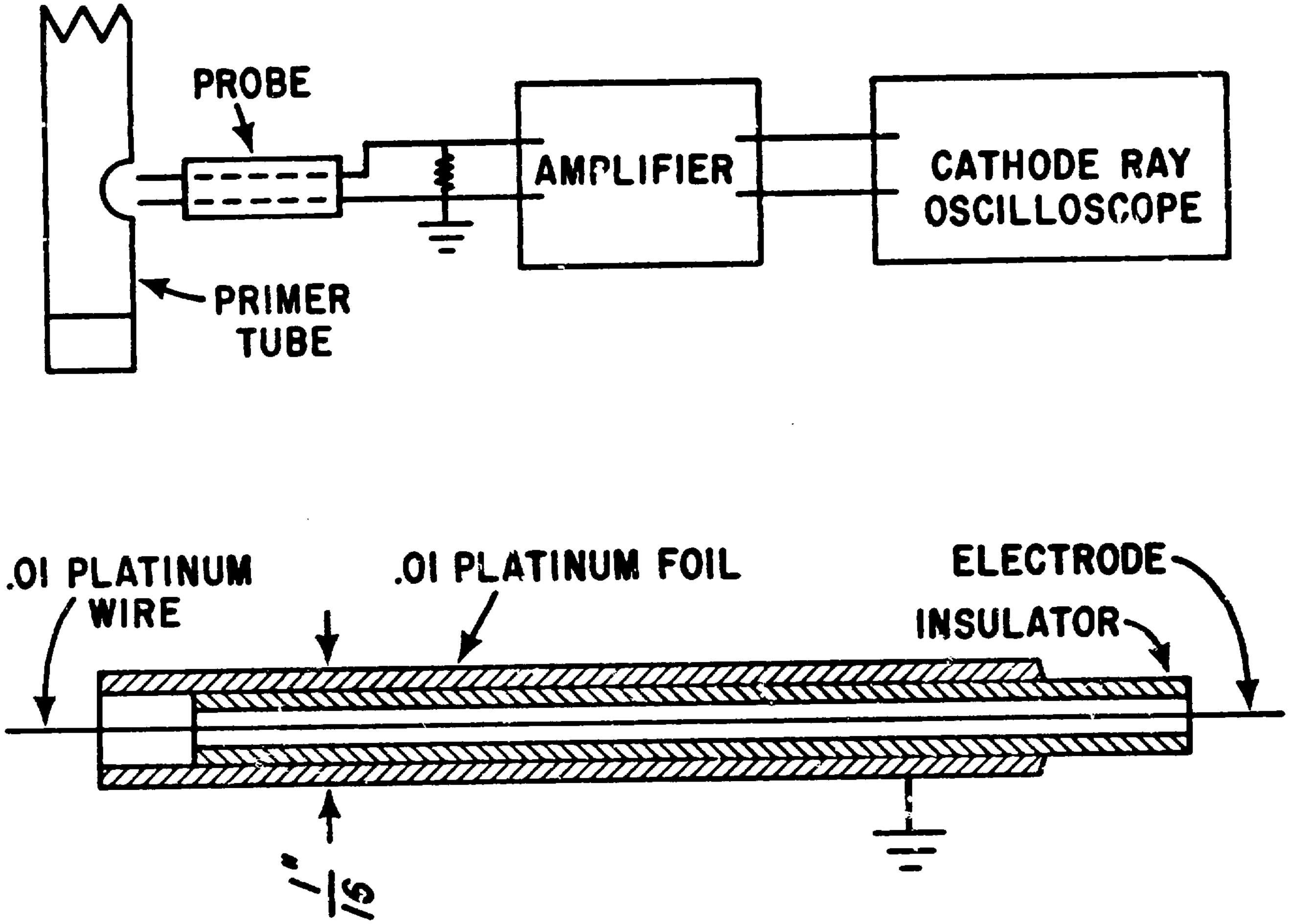

Fig 17 Schematic diagram of ionization gauge