The Flow of Gas under High Initial Pressures. Part I

By C. Cranz and Br. Glatzel

(Translated from Annalen der Physik, Vol. 43, p. 1186, 1914, by N. U. Mayall)

Introduction

The phenomena of the flow of gases from nozzles have been the object of many experimental and theoretical investigations; especial mention is made here of the work of E. and L. Mach, Emden, Prandl, Mazin, Meyer, Steichen. In the case of all these works, it was always a question of the flow process being fixed for the case of a large reservoir gradually discharged, so that attention was given the possibility that, within the time of observation, the pressure in the reservoir did not change. Accordingly, Prandl and his students always based their computations on the assumption that all flow lines come from a space in which a constant pressure prevailed, and in which the velocity of the total mass of gas is not essentially different from zero. Hence there resulted very good agreement between theory and experiment. Naturally the experimental tests of the deduced laws could extend only to relatively low pressures of several atmospheres if the assumptions made should hold, since otherwise the reservoir would have assumed too large dimensions. On the other hand, it appears to us worthwhile to investigate the phenomena of the flow of gases under extremely high pressures, of more than 100 atmospheres.

The apparatus would be relatively simple if a gun were used, for in this case the gases flow out under high pressure after the bullet. There was also the possibility of bringing into the field of the investigations, at the same time, several problems hitherto of a ballistic nature. The relatively simple experimental apparatus had the defect, however, that it did not permit the formulation of clear conditions for a theoretical treatment of the question, so that we were compelled to investigate, first in a purely experimental way, the process concerned, and frequently to give up these questions to numerical approximations.

Experimental Apparatus

A gun of 8 mm. caliber and its ammunition with smokeless powder was used. In general it was discharged with normal loading. Experiments with weaker loading and correspondingly lower pressures gave no significant difference in the behavior of the phenomena. Since this process took place in very short time intervals, it could be photographically recorded only by the use of spark photography. Furthermore, since the flow phenomena become evident principally through density changes, spark photography must be combined with schlieren methods, as had already become apparent in several of the above-mentioned earlier works. Two methods were available for this method, the Toepler schlieren method and socalled shadow procedure of Dvorak and Boys. The latter method is one which, without any kind of an intermediate lens system, traces out a silhouette of the process on a screen brought quite close behind the orifice. Hence it is advantageous to use the smallest possible point source of light at a large distance. There is a most favorable distance for the photographic plate which is best found by trial.[1)] The air strata that are produced act like lenses, which briefly refract the light, so that behind an optically thick spot the air produces a dark shadow, while the surroundings are more or less bright. Therefore, in the photographs an optically thick

1) In general we had 90 cm. for the distance of the plate from the light source, and 10 cm. from the orifice. As a light source, we used a spark between magnesium electrodes, and, of course, the spark gap was so placed that the path of the spark was in the direction of a plumb-line from the spark gap to the plate, in order to attain a point-like action. If spark gaps are used in which the path of the spark is vertical to the line joining the spark gap and plate, then it is of great importance to see that the light glow, which always forms at the electrodes and is relatively slow, be covered up by suitable diaphragms. If this is not done, then it is easy to obtain somewhat indistinct pictures. In the case of the first-mentioned apparatus used by us, this error did not enter seriously in the phenomenon.

place is rendered by a dark shadow, an optically thin one by a light shadow. From the behavior of the shadowing, the behavior of the density variation can in turn be deduced. If the term "Shadow method", which is established in the literature, is perhaps not quite correct, then the pictures taken must be optically similar with high approximation to the actual ones. But since contrary views have been expressed whether Dvorak's method is really valid, we have made a large number of photographs by the Toepler schlieren method under the same experimental conditions, but we have not been able to establish any significant differences. To be sure, the Toepler schlieren method is considerably more sensitive than Dvorak's, although this was found to be a disadvantage in the present case, since the many irregularities only make precise measurements more difficult. The photographs by Toepler's method are, however, more beautiful to the eye. Figs. 1 and 2 (see Plates XI and XII), which were taken under the same conditions, illustrate this better than longer explanations. Finally, the electrical apparatus of the experiment, Fig. 3, and the method used by us to trigger the illuminating spark, may be given in a few words. F_1 is the illuminating spark gap, G the gun, and P the photographic plate. F_1 is connected in series to one of two terminals F_2 at the end of a battery of four Leyden jars, which are charged by an influence machine. The terminals F_2 can be placed at any distance from the gun, and can be short circuited by the bullet. For larger distances from the muzzle, more than 200 cm., two wooden frames spanned with tinfoil are used, which were somewhat smaller than the bullet. For the smaller distances, at which the frame would be thrown about by the powder gas emerging from the muzzle in front of the bullet, that is to say, the tinfoil pieces would be torn, we used E. Mach's technique of crossed copper wire, on the ends of which were pushed small glass tubes, which were shattered by the bullet.[1] The condenser C was charged up by the influence machine to such a

1) The method used perhaps first by E. and L. Mach, shooting between two parallel bare copper wires (Bericht der Wiener Akademie, Abt. 2a, vol. 98. p. 1310, 1889), was prohibited in our case, since the hot powder gases could easily cause the discharge between the bare wires too early. With respect to closer details con-

potential that the terminals F_2 just prevented the spark discharge, and hence a discharge through the illuminating spark F_1 occurred only with the passage of the bullet at F_2. Since the initial velocity of the bullet is known ($v = 890$ m./sec.), then by changing the distance of F_2 from the muzzle, the instant for the photographic exposure may be varied or fixed in a very simple way. From the successive photographs, a picture sequence may be collected in a manner similar to that earlier carried out by one of us. It is, of course, possible to use motion picture photographs instead, although we have temporarily abandoned this method since the pictures are relatively narrow, and we are already near the limit of observing phenomena at greater distances from the muzzle. Besides, it is also apparent that the deviations of different shots lie entirely within the limits of measuring errors.

Two adjacent spark gaps and two objectives will be considered later in the case of stereopscope bullet photographs taken by the Toepler schlieren method.

1. Description of the Flow Phenomena of Powder Gases from Gunshots.

5 In order to explain the origin of the flow pattern, as it is represented in Fig. 2 (Plate XI), it is first necessary to obtain the velocity distribution of the streaming gas particles within the pattern. Since the motion of the individual gas particles cannot be made directly visible in the case of normal shots, nor by means of the schlieren method, there remains only the possibility of measuring the velocity by indirect means. We therefore proceed in the following manner: A fine steel point is placed in a vertical plane through the bore-axis and in the flow pattern, in such a way that its point is located at the place at which the velocity is to be measured, and its direction approximately in agreement with that of the flow lines. Since it was established by several experiments that these in general emanated from the center of the muzzle, the above condition was satisfied without difficulty. Now if the gases flow against the fine point, then at this place there are formed Mach "head-waves" which permit the velocity of the gas particles in the vicinity of the point to

be determined from the velocity of sound present there, according to the law $\sin \alpha/2 = c/v$, where α is the angle of the Mach wave, c the velocity of sound, and v the velocity of the gas particles. The origin of the Mach wave is explained by means of Figs. 4 and 5. The bullet point is able to run through the series of points 1, 2, and 3, with a velocity v. From each of these points, and hence from all intermediate ones, sound waves go out with the velocity c, which, if the bullet has arrived at point 3, have reached the positions shown in Fig. 4. The envelope of those individual elementary waves is the Mach wave, by which means there results the above relation for the ratio of c and v. This origin of the wave from the individual elementary waves is especially well shown in Fig. 5 (Plate XI). It is now completely immaterial for the behavior of a wave whether it is assumed that the bullet point is moving in stationary air, of whether the moving air flows against a point. The greater is the flow velocity, the smaller is the angle. If the velocity decreases to the velocity of sound, then α attains a value of 180°. In this experiment, of course, only those velocities were measured which were greater than the velocity of sound, which was the case, for example, within our flow pattern nearly out to the compression lines. The method gives, in addition to the velocity, the inclination of the flow lines which at the time go through the point of the probe about the bore-axis, so that it was possible to establish not only the velocity distribution within the flow pattern, but also the character of the flow lines themselves. The accuracy with which the various flow lines converge toward the muzzle is quite good (see Fig. 8), so that we may consider our method of measurement perhaps as quite accurate. Also other velocity measures, which will be further explained below, likewise show a high degree of accuracy. For the practical application of the method it is of great importance to give to the point quite a definite thickness. If the point is too fine, only very faint waves are obtained, or none at all in the case of low velocities, while with too broad a point, the formation of the waves likewise may be affected too much, so that in this latter case it must be considered that disturbances in the behavior of the flow lines can be produced by the presence of the probe. The necessary fineness of the point can best be established by experiment. Finally, it may be mentioned that, considering the symmetrical form of the flow pattern, it was only necessary to investigate one half of it with the probe. It was inserted as close as possible to the bore-axis, such that the bullet still could pass freely over the probe. Fig. 6 shows a photograph in which the probe is located in the middle part of the flow pattern, and Fig. 7 one from which there resulted a measurement closest to the compression wave, where the velocity is considerable less than in the middle. Accordingly, the angle α of the wave at the point of the probe is considerably smaller in Fig. 6 than in Fig. 7. Since the wave is formed not only at the point, but also it its farther surroundings (see Fig. 6), then from the curvature of the wave it may also be understood that the velocity of the gas particles decreases with greater distance from the muzzle. For the measurements, however, only the straight part of the wave in the immediate neighborhood of the point was utilized. The diagram of Fig. 8 illustrates, on the basis of the results of measurement[1], in its upper part, the numerical values found, as well as the variation of the velocity along a typical flow line A. The flow velocities are given in numerical values calculated on the basis of the velocity of sound v = 334 m./sec. In reality this value should be different, since it would be considerably changed by the pressure prevailing within the flow pattern, as well as by the higher temperature of the gas. For clarity, however, the gas velocities are given in absolute numbers. We intend to give the size of the necessary corrections as soon as we are able to obtain closer estimates of the temperatures and pressure relations within the flow pattern. The diagram shows, first, that the velocity of the gas particles increases from the muzzle out to about the middle of the flow pattern[2], and then rapidly decreases; second, that

---

1) The points of measurement were established by means of a model of the flow pattern in space fastened to the muzzle of the gun.

2) In the most immediate neighborhood of the muzzle, where for practical reasons no measures can be carried out, considerably smaller velocities must be present.

the flow lines radiate as diverging straight lines from the muzzle. These latter facts we can confirm by a photograph, reproduced in Fig. 9, in which we have made the flow lines directly visible. This was accomplished by removing the bullet from the cartridge and by replacing it with a wad in order to retain the powder in the shell. Then if this cartridge were used for ignition, the burning of the powder was not all complete as a consequence of the essentially lower pressure, and a large number of unburned powder particles flowed out of the muzzle, making the flow lines recognizable.

The probe method may also be used to demonstrate the pressure difference in the flow pattern in contrast with the surrounding air. If the probe is brought very close to one of the compression lines at the side, then the waves originating at the point of the probe are formed not only within the compression line but also outside it, the waves being broken in the manner shown in Fig. 10. Measurement of the interior wave-angle α and the exterior angle α' gives the ratio of the velocities of propagation of the gas particles within (v) and without (v') the flow pattern:

$$\frac{\sin \alpha/2}{\sin \alpha'/2} = \frac{v'}{v}$$

This ratio of the velocities of propagation probably offers the possibility of obtaining the pressure within the flow pattern, which in turn would permit an inference of the gas pressure at the muzzle. We intend to treat these questions in a special paper. For the production of the flow pattern, whose investigation is of the most importance to us in the present work, it is important, since it agrees with the rest of the results, that the pressure difference at the compression lines is quite large, and that these lines should represent a really sharp boundary of the flow pattern.

We can now proceed to explain in detail the origin of the flow pattern as it is schematically represented in Fig. 11.

When the body of the bullet just leaves the muzzle (Fig. 12), gases compressed to about 300 atmospheres are mechanically necessary to take the path indicated by the arrows, because of the resistance which the bullet offers to them. We will designate a velocity vertical to the longitudinal bore-axis as the transverse or cross velocity, and one in the direction MNP of the bore-axis (Fig. 11) as the longitudinal velocity. As soon as the bullet is away from the muzzle, the gas particles flow freely into the air. Since the gas pressure thereupon falls, and at first little energy has been lost by friction etc., then the velocity of the gas particles increases until, as a consequence of the energy loss becoming stronger partly because of friction on the surrounding air particles and partly because of doing work of compression, it gradually decreases. This work of compression, which requires the greater part of the energy, is used up if the flowing powder gases compress the air in front of them. This occurs until the gas pressure produced by the existing elastic air compression prevents a further acceleration of the air particles. The air is therefore dammed up at the place CPC_1 (the so-called Stodola compression-shock), and this dam or piling-up lies farther from the muzzle in the case of high pressure than for low pressure. As a result of this the dam always moves back towards the muzzle with gradually decreasing pressure, and finally apparently disappears in it. The migration velocity of the dam is therefore a direct measure of the pressure variation in the muzzle. The series of photographs of Fig. 13 shows this phenomenon for the time interval during which the bullet had moved from the muzzle out a distance of 3 m. The numbers indicated in the individual pictures denote the distance of the triggering spark F_2 (Fig. 3) from the muzzle in decimeters. In all of the photographs it may also be noticed that the image of the compression line is shadowed dark toward the muzzle, and bright away from it. Accordingly, the density or congestion of air is greater on the side of the compression line facing the muzzle. The increase in pressure is steeper here, and outside gradually decreases. It is perhaps useful to draw an analogy for the explanation of the compression line CPC_1, which is observed in the case of flowing water[1].

---

1) Our attention was brought to this analogy by Baurat Beyerhaus (Versuchaustalt für Schiffs und Wasserbau in Charlottenburg).

At a watergate AC (Fig. 14a,-b), the water above stands at the height h_1, and below at h_2. The sluice gate is pulled up so far that water from the opening BC (Fig. 14b) flows out. If no friction were present, then the water in the region BCDE would flow farther underneath the stationary water GBDF. In fact, however, friction exists between the flowing water and the stationary water. As a consequence stationary water above BD is dragged along by the flowing water below BD, and the result is that the water-level is lowered some distance from G, so that a piling-up is seen at M. The smaller is the pressure-head difference h_1-h_2, the smaller is the exit velocity of the water from the opening BC, the farther back toward BC is this congestion M, and conversely. Also, the steepest slope lies toward the exit opening.

A compression line analogous in our case is the line CC_1 (Fig. 11), the wave crest of a relative pressure maximum that originates by the impact of the powder gas coming from the gun against the opposing relatively stationary outside air. This plate-shaped wave crest therefore is produced by the rapid increase of the compressed outside air together with the powder gases; depending on whether this plate is or is not sharply projected in the photographic exposures, it is seen as a flat ellipse or straight line.

Since the gases within the angle MCC_1 (Fig. 11) flow essentially with only longitudinal velocity, the line CC_1 is approximately vertical to the bore-axis.

We now consider those gas particles whose flow lines lie outside the angle MCC_1. In the case of these, an appreciably larger transverse velocity component is present than in the case of the particles moving in the close vicinity of the bore-axis. This component is independent in magnitude of the inclination of the flow lines, as well as of the absolute value of the flow velocity. The inclination of the flow lines, which lie in the regions MAB and MA_1B_1 (Fig. 11), however, is greater, and consequently the transverse velocity component is also relatively large, although the orbital velocity of the gas particles themselves is smaller at first. Behind the middle of the flow pattern there exists so rapid an increase of the flow velocity[1)]

1) A measure for the size of the transverse velocity comes from the fact that the blast of a strong air-flow from a bomb with about 10 to 15 atm. across the flow form is able to exert no appreciable influence on the position of the ...

(see Fig. 8), that this reduction of the transverse velocity component, because of the lower inclination of the flow lines, not only balances but even requires an increase of the transverse velocity component. As a result, the transverse deviation which the air particles experience is likewise increased toward the center. This transverse deviation reaches its maximum about at B (Fig. 11), and then quite rapidly decreases because of the action of the compression CPC_1. The behavior of this transverse deviation results in the formation of curved compression lines in the same way as in the case of CPC_1. Also, these lines are wave crests, that is, geometrical positions of relative pressure maxima, originating through the compression of the outside air by the expelled powder gases. Since it is a question here of relative maxima, there is nothing to prevent the occurring of additional wave crests simultaneously in succession or into each other (see Fig. 21). It may be seen, therefore that, in the case of the flowing out of the powder gas, the outside air because of its inertia and elasticity plays a role similar to a piece of rubber tubing, which is fixed to the end of a pipe, and squeezed out at the other, as an elastic elongation of greater cross-section. At the places at which the side compressions ABC and $A_1B_1C_1$ and the transverse compression CPC_1 occur, the transverse velocity is relatively small. As a result, the compression here is not so great, as may also be seen from the lesser darkening of the compression lines in Fig. 2. The flow lines thus go through these compression places with considerably higher velocity, and then produce the appendages CD and C_1D_1, which, therefore, likewise represent compressions.

In the case of all these considerations, the conceptions "Flow Lines" and "Compression Lines" must be carefully distinguished. The flow lines go through the compression lines, in exactly the same way as in the case of the water flow. The two quantities correspond in a certain sense with the conceptions of current and voltage in electricity. The measuring or the visibility of the compression lines results from schlieren observations, that of the flow lines from the above-described probe-method with the aid of Mach waves. Nothing, of course, prevents the appearance of these compression waves in the midst of a turbulent motion, for example, in a mixture of air and turbulent powder gas like that produced in the case of a shot.

A photograph that shows the compression lines as well as the flow lines, with the latter again made visible by unburned powder flakes, in the same way as before without shooting a bullet, is reproduced in Fig. 15. Furthermore, the elasticity of the surrounding air appreciably influences the position of the compression lines, as is shown by an experiment in which a wooden wall is placed below the bore-axis and quite near to the place where the compression CPC_1 exists. The resistance that this wall produces, gives the result that the part of the compression line CPC_1 lying in front of it toward the muzzle is bent there, as is shown in Fig. 16.

The formation of the flow pattern described above can also be obtained similarly to that of the Mach waves by means of a reversal of the experimental conditions. In the case of the previous apparatus, the gases flow out from the stationary gun muzzle. If the muzzle is now moved very rapidly against the stationary air, then the same flow pattern must be obtained. In fact, this is also the case if a hollow bullet[1)] is used, and this photographed in free flight[2)]. Fig. 17 shows that one of the earlier, similar compression patterns is formed behind the bullet.

Besides the previously-illustrated processes outside of the muzzle there occur peculiar contraction and broadening phenomena of the discharge itself, which will be briefly considered, although they were, in fact, in Fig. 13, which represents the form of the flow process at different times. While the shadow image of the discharge is sharply limited in the case of a photograph without a bullet, picture 1 of Fig. 13 shows a strong bulging-out which is brought about by the out-flowing gases. the density of these gases is so great that their shadow on the photographs cannot be distinguished from that of the surrounding air. This bulging, which is indicated only very faintly in the beginning, increases to a maximum. There is gradually formed in the center a contraction, (beginning in picture 2), which in turn increases for a time and attains its maximum value about in picture 3. Later, a dark point is formed in the middle of this contraction (pictures 5 and 6), until finally, at

1) After preparation of this paper, we learned of a similar photograph that Hyde in North America had taken (Ordnance Pamphlet, Navy Dept., 1913).

2) A method for the triggering of the spark was used here which has been published by one of us in "Schuss und Waffe", vol. 6, p. 400, 1913.

later instants when the pressure has decreased to small values, the discharge again appears to be outlined exactly as it was before the shot was fired. In the beginning of this work, in the discussion of the use of schlieren methods, it was shown that, with the photographic methods used, every darkening in the schlieren image corresponded to an air compression, and every brightening to an air expansion. Therefore, we have on our photographs, soon after the bullet has left the barrel, a strong compression of the expelled gas particles, which at first increases and then some time later is transformed into an air expansion. Hence there occurs a negative pressure in the discharge whose presence has already been established experimentally by one of us. If down feathers or tow (coarse and broken part of flax, hemp, or jute ready for spinning) are piled up in the first part of the bullet path all the way up to the muzzle, and the shot is fired, then the light, moving pile is seen to progress back toward the muzzle. After the shot, the muzzle is covered and individual down feather particles or tow threads are drawn into the muzzle. With this result, the sequence of density variations observed by us in the discharge, now are entirely harmonized. Also, stereoscopic photographs of the flow pattern, which we have made by using two spark gaps placed together, likewise reveal the existence of a rarefaction in the discharge. There stereoscopic pictures in addition show the compression pattern as an approximately oval surface, and transparent as glass. In the inside, the air striae present there appear to be freely suspended, so that an extremely delicate and beautiful form is seen. A similar flow figure has been obtained by Günther and Külp with foreground illumination and stereoscopic photographs.

We now come to the results of measurement of the pressure variation in the outflowing gases. As already pointed out above, the migration velocity of the principal compression line perpendicular to the bore-axis is a measure of the course of the pressure variation in the discharge. It is, however, not possible to calculate the absolute pressure from the distance to the compression line without further data. For low pressures and continuous flow of gases, in the case of which there occurs, because of elasticity, a wave structure in the surrounding air of such a nature that the compression lines are repeated several times within the stream, a formula has been advanced by Emden and then by Prandl which permits the calculation from the wave length—the distance between two successive compression lines or of the first one from the muzzle—of the pressure produced in the exit nozzle, in good agreement with the results of measurement; however, as was mentioned in the beginning, the basic underlying assumptions of the calculation in the case of our experimental arrangement are so little fulfilled that there is not much use to apply the formula in the present case. We have, therefore, limited ourselves for the present to the determination of only the relative run of the pressure change, measured for the time being by the distance of the compression line from the muzzle. The result of the measures is graphically represented in Fig. 18, for a shot with S-bullet and normal loading in Curve 1. It is seen from this that the distance of the compression line in front of the muzzle, and therefore the pressure in the muzzle, or, more exactly expressed, the ratio of the gas pressure in the tube in front of the muzzle to the gas pressure outside the muzzle, at first increases and then decreases relatively rapidly.

Associated with this phenomenon is the question of under which circumstances the velocity of the bullet after leaving the muzzle is still further accelerated a distance by the pressure of the outflowing powder gases. For cannon, C. Crehore and O. Squier, for guns W. Wolf, M. Rodakovic, and especially recently M. Okochi, have concerned themselves with this question. We intend to return to this in Part 2 of the work[1].

Earlier velocity measurements by the probe method lead to the same result: that the pressure ratio, and hence the ratio of the flow velocity to the velocity of sound, at first increases and then decreases; in this case, the experiment was carried out in such a way that the probe was placed at a fixed distance from the muzzle, and at different time intervals after the shot the instantaneous velocity was obtained from the Mach waves that formed. Curve 2 in Fig. 18 shows the run of the velocity variation. The velocity is at first small—the curve when extra-

1) More exact references to the lit...

polated runs to the point of the ordinate axis which corresponds to the velocity of sound, 334 m./sec.——then increases and later gradually decreases. To the small initial velocity, in the case of initially constant energy, there corresponds a high pressure which then decreases with increasing velocity, and finally, if a further consumption of energy occurs, diminishes still more. If a Maxim silencer is now placed on the muzzle of the gun (Curve 3), then the velocity of the powder gases in the spiral turns of the silencer is appreciably reduced, and at the same time a considerable part of the energy of the powder gases is consumed. The result of this is that the pressures occurring at the muzzle of the silencer are much less than in the case of shots without the silencer. From this it is also evident that the pressure variation is not nearly so sharp as in Curve 1. As a consequence the surrounding air gets no sharp blow as in the case of shots without a silencer, which is the principal cause for the reduction of sound by the Maxim silencer. Curve 4 finally was obtained with decreased loading of 2 grams (compared with 3.2 grams in the normal cartridge), and shows a run similar to the other curves.

Along with these experiments with the silencer, we have made several others with tube attachments of greater diameter than the bore, which, however, are not yet completed. Nevertheless, several results have been obtained that seem to us worth mentioning. The waves cross inside the tube, as Prandl and his students already have observed, and have used for purposes of measurement. Furthermore, the powder gases flowing out strike against the sharply cut-off edge of the attached tube and produce Mach waves there, which, as indicated in the schematic Fig. 19, can result in intersecting compression lines in the interior of the flow pattern, similar to those mentioned earlier. These Mach waves at the edge of the attached tube are especially plain in the schlieren photograph of Fig. 20. These compression lines are so pronounced——a fact which depends particularly on the length and diameter of the attached tube——that they run far into the principal flow pattern and there strike against the outside compression lines. Since in these the outside air is strongly compressed, they suffer a reflection here, and then run back again to the inside of the flow pattern. In this way crossed waves originate within the principal flow pattern, which can be repeated, under these circumstances, many times within the gas stream. If the length of the attached tube is changed, or if the shot is observed at different times, then since the angle of incidence of the flow lines to the edge of the attached tube is thereby changed, the crossed waves proceed from the muzzle with different angles, occasionally with such angles that a crossing no longer occurs, as is the case, for example, in Fig. 21. These crossed waves described here also can occur with automatic guns, in which the barrel slips back in the barrel-casing after the shot. In this case the extended barrel-casing plays the role of the attached tube. Crossed waves of this kind in the flow pattern have previously been observed in this connection, without, however, the cause of them being explained.

While the preceding results concerning the outflow of powder gases refer for the most part to relatively late time intervals at which the bullet has already left the barrel, we shall consider in Part II of this wark chiefly the phenomena which pertain to the outflow of those gases which leave the barrel before the bullet. Since these investigations, however, are more of a ballistic nature, and also require special new arrangements for triggering the spark, we have separated them from the preceding published Part I.

The investigations were carried out in the ballistic laboratory of the Military Academy at Charlottenburg.

Berlin-Charlottenburg, Dec. 1913.

Sketches

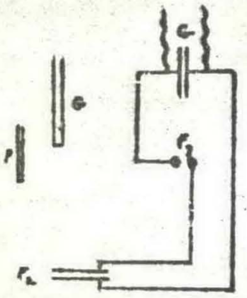

Fig. 3

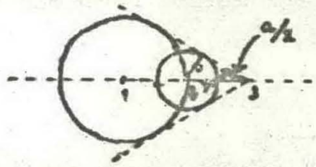

Fig. 4

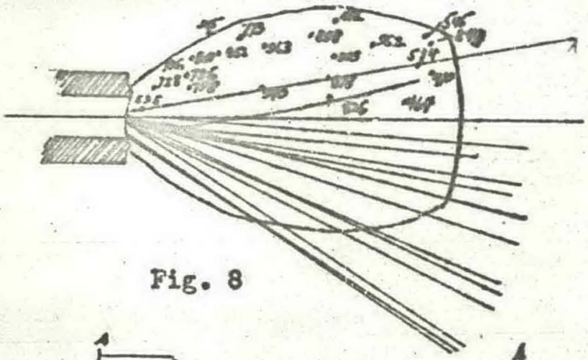

Fig. 8

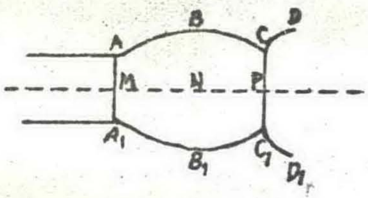

Fig. 11

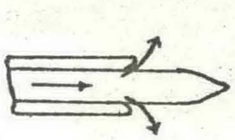

Fig. 12

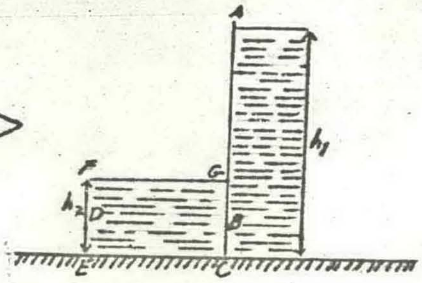

Fig. 14a

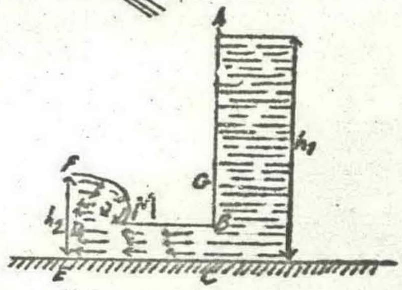

Fig. 14b

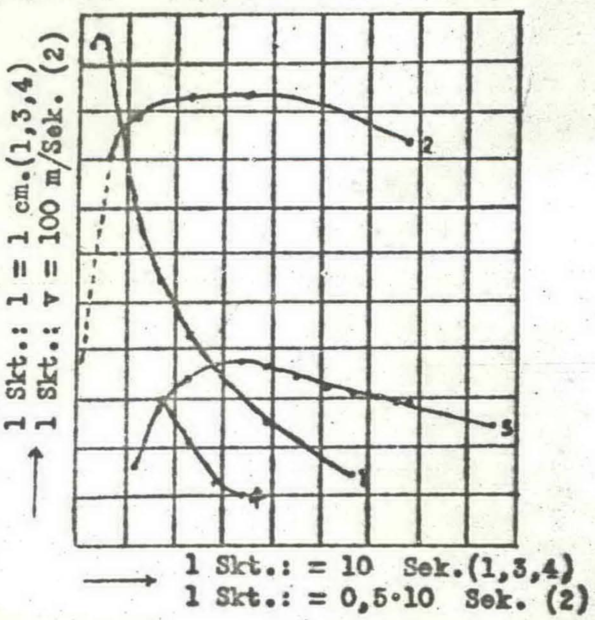

Fig. 18.

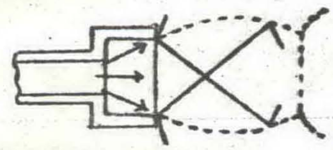

Fig. 19

Fig. 1.

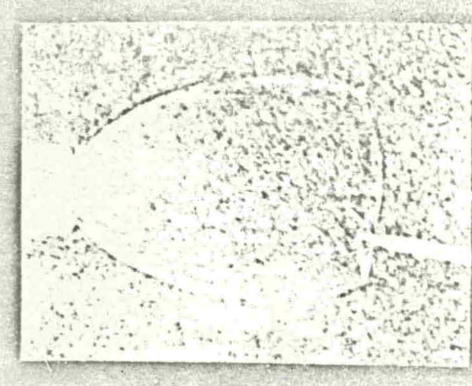

Fig. 7.

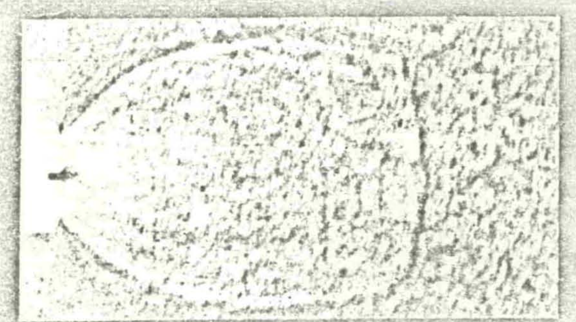

Fig. 2.

Fig. 9.

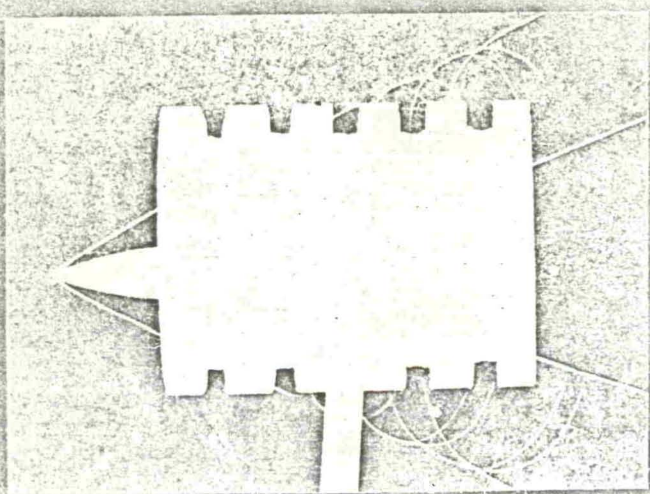

Fig. 5.

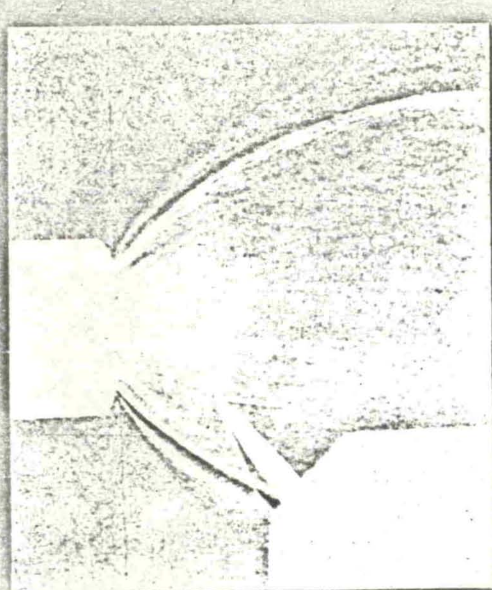

Fig. 10.

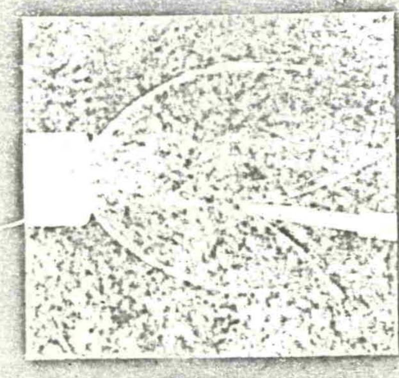

Fig. 6.

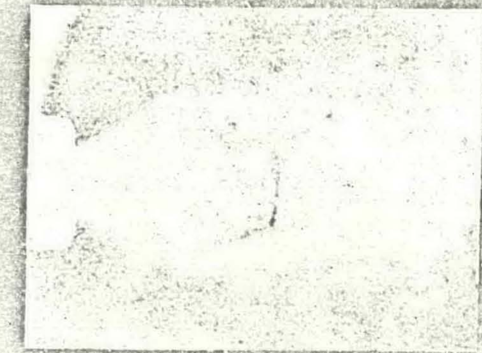

Fig. 15.

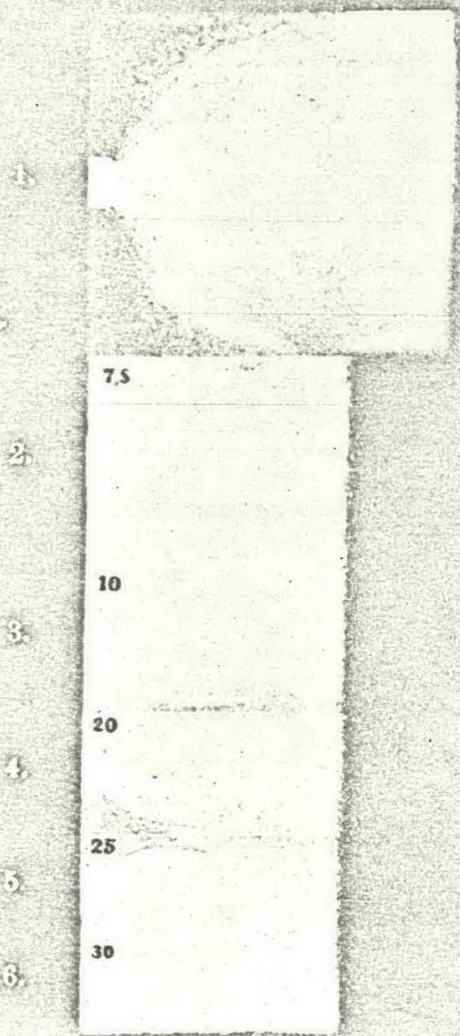

Fig. 13.

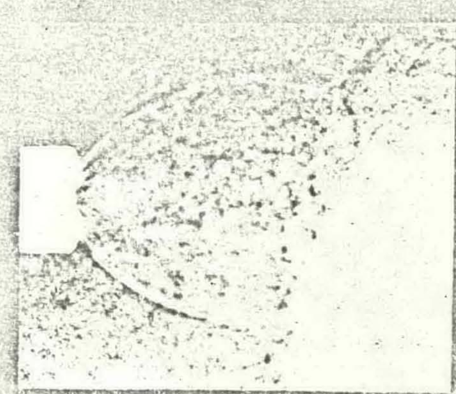

Fig. 16.

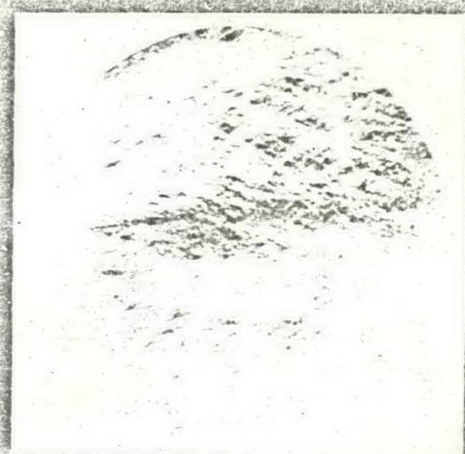

Fig. 20.