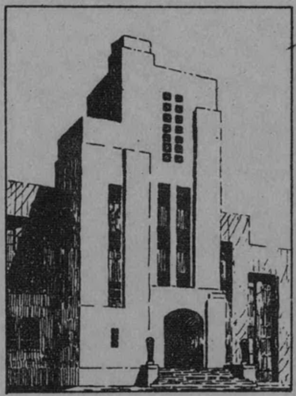
THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

RECENT RESULTS IN SPARK CINEMATOGRAPHY

BY H. SCHARDIN AND W. STRUTH



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RECENT RESULTS IN SPARK CINEMATOGRAPHY

(NEUERE ERGEBNISSE DER FUNKENKINEMATOGRAPHIE)

by

H. Schardin and W. Struth

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The David W. Taylor Model Basin
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RECENT RESULTS IN SPARK CINEMATOGRAPHY

ABSTRACT

A recording apparatus with which it is possible to make 24 successive images of a high-speed phenomenon up to frequencies of images of several millions per second is described. These 24 pictures are enough to reproduce the phenomenon on film. Photographs of missiles shot through wires, against armor plate, through plastic mediums, and through water are given and discussed.

The method permits a new type of insight into the phenomenon of the propagation of cracks in glass and into the production of implosion pressure waves.

In the years 1927 and 1928, C. Cranz and H. Schardin developed a spark cinematographic apparatus to investigate high-speed phenomena, especially such as those which occur in ballistics. This device, whose image frequency runs to several millions per second, was described in the Zeitschrift für Physik (1)* for 1929. At that time a number of experiments were made with this instrument which registered 8 successive pictures of the phenomenon. Later, through the support of the Research Aid Council, a more carefully constructed apparatus in which leyden jars were replaced by cylindrical condensers for the formation of 9 illuminating sparks (Beleuchtungsfunken) was constructed. The new device was introduced by H. Schardin at the Founder's Day meeting of the Society for Photographic Research in Berlin in 1929. For a considerable period it was used for minor research problems.

After it had been proved that the apparatus was very reliable and comparatively simple to operate, the desire arose to construct such an instrument to record a sufficient number of individual images to reproduce the phenomenon on motion picture film. Twenty-four images appeared to suffice for this purpose. At a frequency of projection of 16 pictures per second, the film would have had to run off in 1.5 seconds. However, it was expected, and was later verified, that the impression of uniform motion is well maintained if the same image appears on the screen twice in succession. The phenomenon then, requires 3 seconds to run its course. This is quite sufficient to comprehend the phenomena recorded, as proved by the strips of film which were exhibited at the Physicists' Convention in Bad Kreuznach.

These pictures were taken with an apparatus for making 24 images, like that completed a year previously in the Ballistic Institute of the Aeronautical Academy at Berlin-Gatow. Julius Pohl was chief participant in its construction. It shows a number of improvements over the former apparatus which will be reported elsewhere.

The strips of film are used primarily to show ballistic phenomena: The impact of projectiles on solid, plastic, and fluid mediums as well as the phenomena at

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* Numbers in parentheses indicate references on page 10 of this translation.

the muzzle of a gun when fired. However, these are all physical phenomena of unusual magnitudes, i.e., they involve extremely high pressures and velocities and extremely short periods.

However, a flying projectile can also be used to start certain physical phenomena at a desired time, such as the propagation of cracks in a glass plate or the inception of implosion pressure waves in water. These will be discussed later. Therefore, a firearm or rifle can be designated as a physical apparatus and is, moreover, used as such in the lectures of well-known physicists. However, when handling a rifle, as Privy-counselor Zenneck humorously emphasized after the lecture, a certain amount of care is necessary to prevent accidents; exactly the same care is necessary when working with high-tension electricity or with dangerous chemical reactions.

The primary object of strips of film is to give an idea of the mechanical progress of the phenomena which occur at high velocities and in which mass inertia plays the major part. However, with the aid of high-frequency motion pictures new scientific knowledge is also gained.

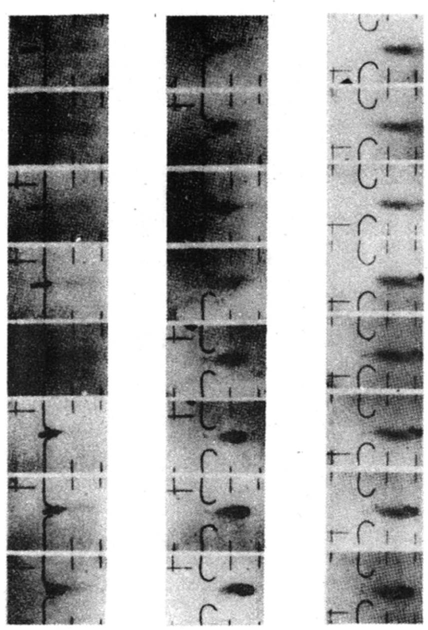

Figure 1 - Twenty-four Successive Photographs of a Bullet Cutting a Steel Wire

The wire was 2 mm (0.08 inch) in diameter; the bullet was steel-jacketed and its velocity was 785 meters per second (2,575 feet per second); the image frequency was 100,000 per second.

WIRES CUT BY PROJECTILES

There are several devices for measuring the velocities of projectiles, which operate by the interruption of a circuit, caused by breaking wires. The object is to learn the position of the projectile when the circuit is broken. Wires of tough ductile material behave very differently from those made of highly brittle materials. A brittle steel wire is simply parted without any important motion of the ends when severed by a bullet, whereas the ends of a normal steel wire tend to curl and roll up and are spread by the projectile even before it has entirely traversed the plane of the wire. Figures 1 and 2 show this clearly.

The importance of mass inertia in these phenomena is especially evident from the photographs of a projectile passing through a suspended steel wire; see Figure 3. The upper end of the short severed end is bent at a wide angle while

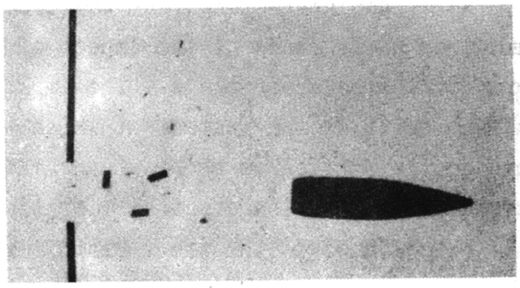

Figure 2 - Bullet Fired through a Brittle Steel Wire

The diameter of the wire was 1.5 mm (0.06 inch).

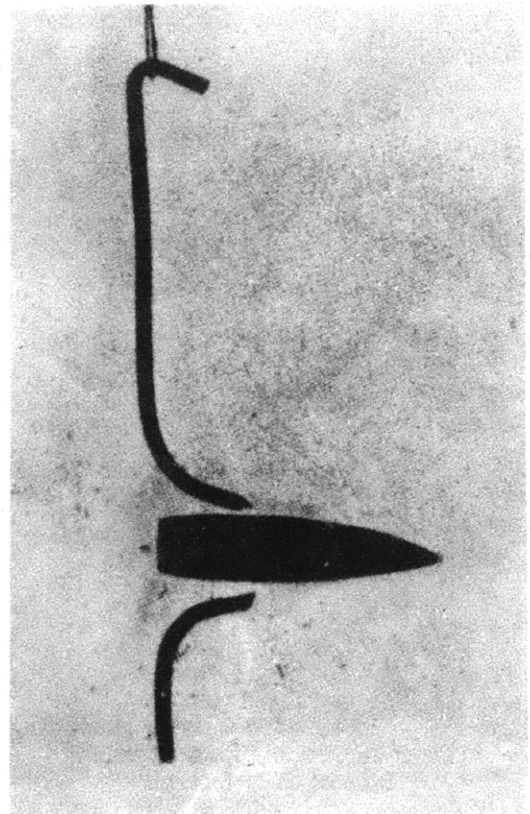

Figure 3 - Bullet Passing through a Suspended Steel Wire

The diameter of the wire was 2 mm (0.08 inch).

the lower end is still at rest. The deformation is produced against the mass inertia of the remaining portions.

PROJECTILES FIRED AGAINST ARMOR PLATE

Individual photographs of shots fired at an armor plate have recently been rather extensively published in foreign countries. However, only by serial exposure at a sufficiently high frequency of images can all the phases of movement in this phenomenon be completely grasped. When a steel-jacketed bullet, i.e., a lead bullet with a steel covering, impinges upon a rather thick armor plate it is completely demolished; see Figure 4. Obviously the lead is partially converted into vapor instantly and spreads along the plate at a velocity greater than that of the projectile, about 1000 meters per second (3280 feet per second). The resultant expansion of the lead vapor is so great that a shock wave is produced. Thus the whole phenomenon has the effect of an explosion.

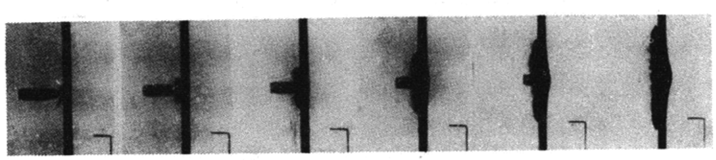

Figure 4 - Six Successive Photographs of the Impact of a Steel-jacketed Bullet on Armor Plate

The velocity of the bullet was 785 meters per second (2,575 feet per second); the image frequency was 145,000 per second.

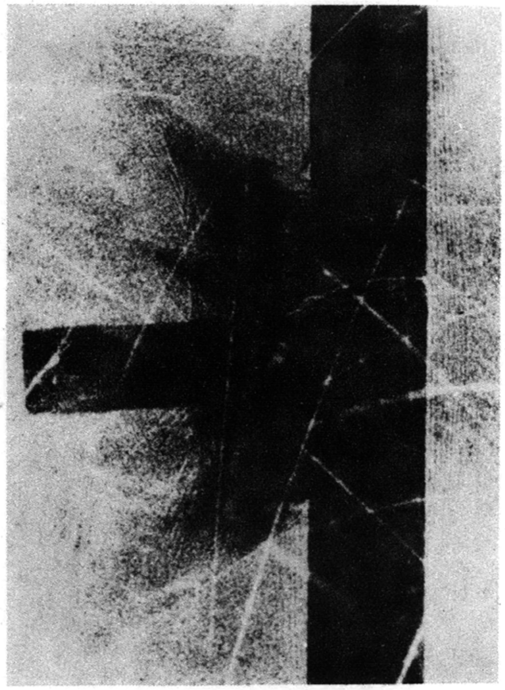

Figure 5 - Supersonic Waves, Emanating from an Armor Plate at the Impact of a Bullet

An interesting fact was determined by photographs of the impact of projectiles on armor plate. The impact which occurs at the instant at which the projectile strikes is so brief and intensive that strong longitudinal vibrations may be produced in the armor plate. The supersonic waves emanating from the plate are visible in some pictures, as in Figure 5, although the exposures were made without any special arrangement for streak photography.

PROPAGATION AND PATTERN OF CRACKS IN GLASS

As will be noted from the photographs, when a bullet passes through a water tank, the glass walls which form two of its sides generally burst. The remarkable fact was discovered that the velocity of propagation of these cracks is absolutely constant, since the boundary of the pattern represents a perfect circle, and that it is much higher than the velocity of the missile; see Figure 15, page 8.

A more precise understanding of the phenomenon was attained by producing the cracks simply by an oblique shock through the glass plate, using a steel-jacketed bullet. A second bullet whose trajectory was above the glass plate, discharged from a special gun simultaneously, permitted the exact determination of the time differential between the photographs. The boundary of the cracks was completely circular in this case also, as is shown in Figure 6.

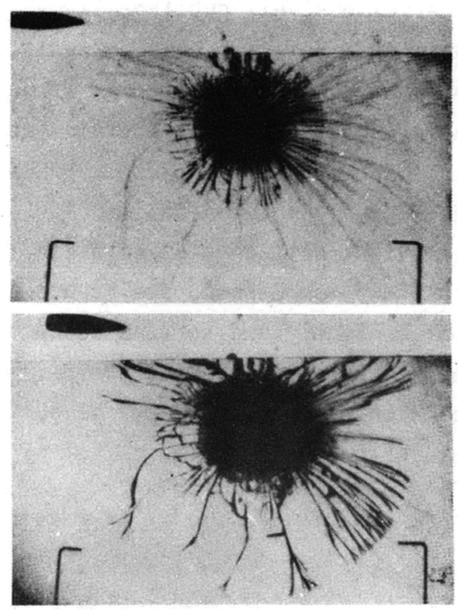

Figure 6 - Bullet Fired through a Glass Plate 4 mm (0.16 inch) Thick

The bullet in free flight above the glass plate serves as a time scale. The time differential between the two photographs is 2.5×10^{-5} second. The distance between the wire markers is 15 cm (5.9 inches). A slight over-exposure occurred on the upper picture; therefore the contours of the further propagation of the cracks can be distinguished.

A velocity of propagation of the cracks of almost exactly 1500 meters per second (4920 feet per second) was obtained for glass plates of various thicknesses without any recognizable effect of the thickness.

Cracks whose course is not a straight line do not quite reach the circle which is to be described as a boundary for the remaining ones. Nevertheless, if the velocity of propagation along such cracks is measured, the same value, i.e., approximately 1500 meters per second (4920 feet per second), is found.

In some photographs cracks spread from a point on the edge of the glass plate at the same velocity, even before this point is reached by the other cracks; see Figure 7. The boundary of these cracks again furnishes a circle with the point of origin as a center. They must obviously be produced by the longitudinal wave traversing the plate at 5,000 meters per second (16,400 feet per second).

Additional experiments of a similar type should offer important contributions to the physics of glass (2).

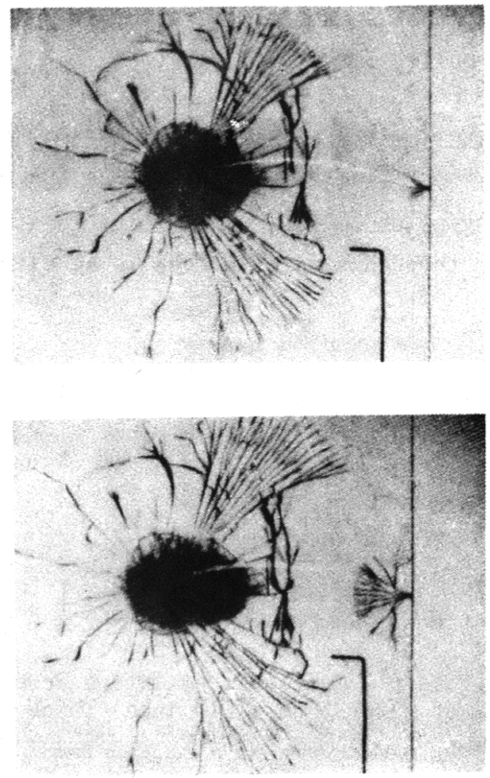

Figure 7 - Bullet Fired through a Glass Plate 2 mm (0.08 inch) Thick

The center point of a secondary fracture develops at the edge of the plate, at the right of the photograph. The time differential between the photographs is 9×10^{-6} second.

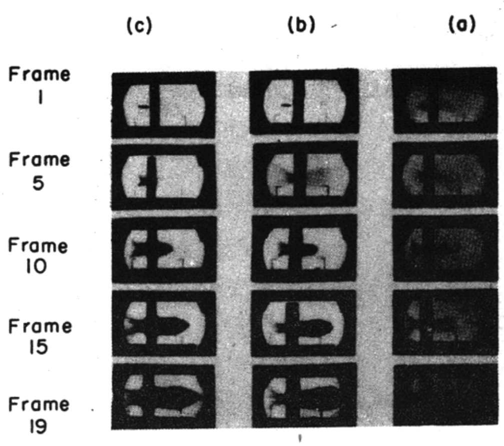

Figure 8 - Effect of a Projectile Passing through a Layer of Damp Clay 3 cm (1.18 inch) Thick

(a) An ordinary steel-jacketed bullet fired nose first.
(b) A steel-jacketed bullet whose tip has been filed slightly flat.
(c) A bullet fired tail first.

The image frequency was 70,000 per second.

PASSAGE OF PROJECTILES THROUGH PLASTIC BODIES

Figure 8 gives a comparison of the effect of a projectile traversing a wall of moist clay 3 cm (1.18 inch) thick. The normal bullet produces a mechanical movement in the clay which is almost symmetrical with respect to the points of entry and exit. In the photographs taken of the bullet which was filed on the point only, the dum-dum effect is clearly recognizable. It is only slightly less than for the bullet fired tail first.

PROJECTILE FIRED THROUGH A SCREEN OF WATER

To make a closer study of the phenomena occurring when projectiles penetrate any type of bodies, simple experiments must be used as a starting point. A bullet shot through a water screen is an example (3). Figure 9 shows the instant at which a

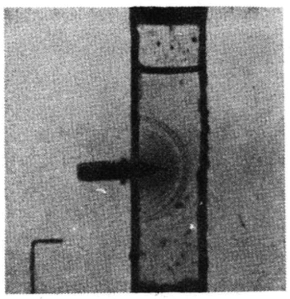

Figure 9 - Bullet Fired into a Screen of Water 3 cm (1.18 inch) Thick

An aqueous shock wave emanates from the point of entry.

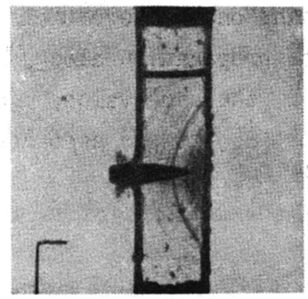

Figure 10 - The Same Phenomenon as Shown in Figure 9, 1.7×10^{-5} Second Later

projectile penetrates a screen or layer of water 3 cm (1.18 inch) thick which was held in place by sheets of cellophane. It can be perceived that a spherical wave emanates from the point of impact. In water, naturally, the velocity of sound, 1450 meters per second (4756 feet per second), is greater than the velocity of the projectile, 785 meters per second (2574.80 feet per second). Hence the projectile can no longer have a head or bow wave in water; the head wave which is present in air precedes the projectile as an independent wave in water. Behind this wave the pressure in the water is raised considerably. The compression of the water also appears to be considerable, since scarcely any bulging of the external surfaces occurs, even though a very considerable volume of water has been displaced by the penetrating projectile. This phenomenon is shown in Figure 10. Several reflections of the wave can be traced on the side surfaces.

The penetration of the bullet causes definite pressure distribution in the screen which results in movements of the water particles. For the normal high-speed steel-jacketed bullet traversing a thin screen of water, the pressure distribution will be approximately equal in all planes normal to the trajectory. Therefore, the type of motion of the water will be almost identical on both the surfaces of entrance and exit of the missile, see Figure 11. Using a normal steel-jacketed shell, damp clay behaves identically. Conditions naturally differ if the front end of the projectile is a surface perpendicular to the path of the projectile. Under such conditions, as the projectile advances through the water, a continually increasing mass of water is accelerated in the direction of the bullet's travel. This occasions much greater pressures and asymmetry of the surfaces of entrance and exit.

PROJECTILE FIRED INTO A LARGE WATER TANK

In the photographs of a shot fired into a large water tank, the waves which precede the projectile and which emanate from the point of its entrance into the tank, as well as their reflection from the surface and the bottom of the tank, are again

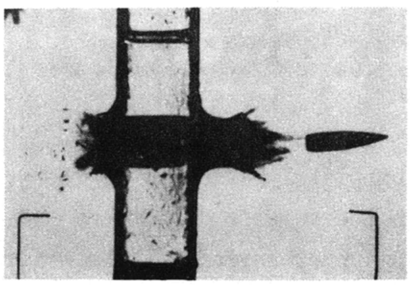

Figure 11 - Bullet Fired through a Screen of Water 3 cm (1.18 inch) Thick

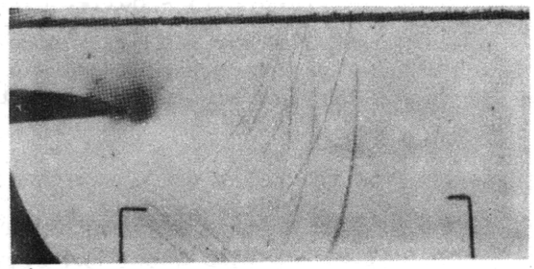

Figure 12 - Bullet Fired into a Water Tank

Note the propagation of the shock wave in water and the cavity behind the bullet.

immediately recognizable in Figure 12. As the result of its high velocity, the bullet draws a cavity along behind it* (4), (5).

The spot at the point of the bullet might be traced to light refraction resulting from the pressure rise in the water in front of the projectile.

The dimensions of the tank used in the experiments were 35 x 20 x 20 cm (13.78 x 7.87 x 7.87 inches). The front and rear of the tank were of shatter-proof glass. The bullet entered as nearly parallel as possible to the surface of the water from a distance of a few centimeters through a frontal wall made of cellophane.

It is interesting to note that almost all projectiles first moved downward. This might be explained as follows: the pressure in the vicinity of the bullet first increases from the top downward, but later certainly also from point to base. Consequently an upward force results which is smallest at the point, and a moment of torque acts upon the bullet. It will assume a somewhat oblique position, with its point directed downward, and partially follow this course, the first effect of which is a downward movement. This also explains the waves which are produced in the upper surface of the cavity, as shown in Figure 13. These waves originate at the upper corner of the base of the projectile at the instant when this corner of the bullet enters the boundary flow of the water surrounding the tubular cavitation hollow. This point may later also be recognized as a slight buckle in the cavitation hollow, see Figure 14.

Finally as the result of the oblique position of the projectile, the water

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* E. Genning made photographs of cylinders moving through water with a slow-motion camera.

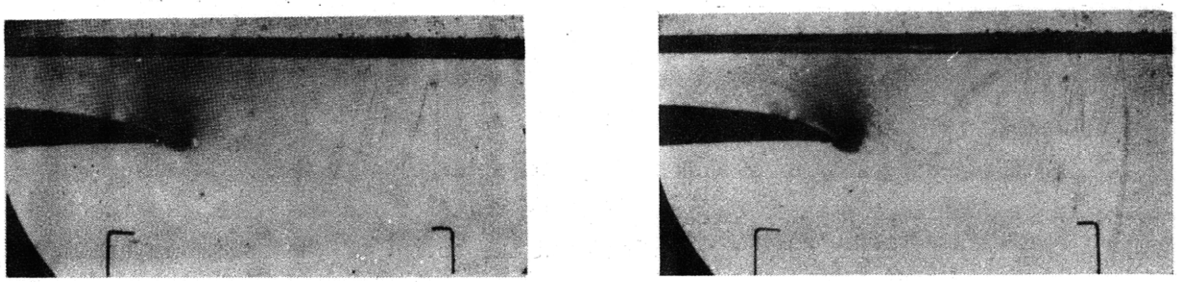

Figure 13 - Bullet Fired into a Water Tank

The time differential of the left hand picture compared to Figure 12 is 2.8×10^{-5} second. Time differential of both pictures compared to each other is 1.4×10^{-5} second. Waves are propagated from the upper edge of the base of the projectile.

will separate from the lower side, whereas it remains completely attached to the upper. This produces a very strong moment of torque in the reverse direction. The bullet is suddenly hurled about and flies out of the upper surface of the water; see Figure 15. The complicated phenomena occurring when a shot is fired into water are naturally not entirely explained by these data. However, they may have contributed enough information to show that high-speed cinematography is an indispensable aid to explain such problems.

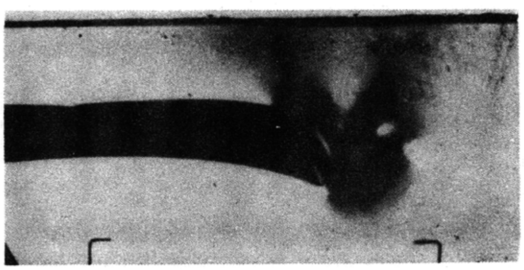

Figure 14 - Projectile Fired into a Water Tank

The cavity behind the projectile is dented at the upper left. At the upper right an implosion of two small air bubbles has occurred.

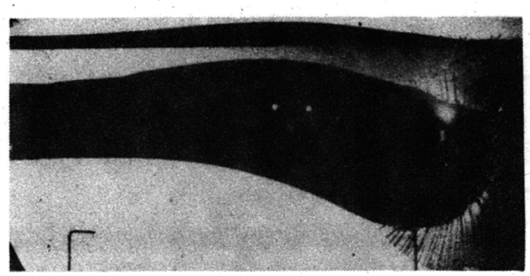

Figure 15 - Shape of the Cavity behind a Long Bullet as it Enters Water

This view shows the propagation of cracks in a shatter-proof glass plate.

IMPLOSION OF AIR BUBBLES

When a projectile is shot into a water container, the water is suddenly subjected to an increased pressure. If air bubbles are present in the water, they must be compressed to a considerably smaller volume. In the process, the water particles along the edge of the air bubbles are sharply accelerated. The kinetic energy produced, however, is immediately re-converted into compressive energy, and the water masses, moreover, will collide violently. Therefore intense pressure waves must be produced.

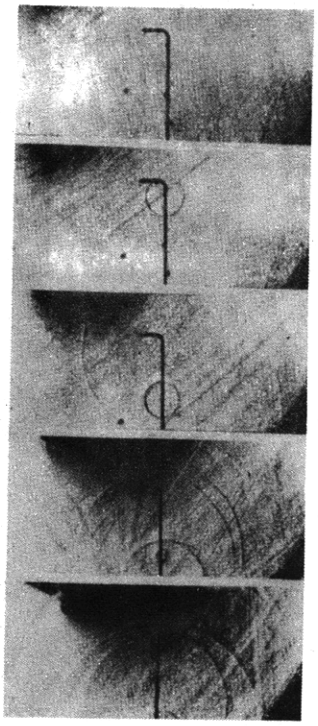

Figure 16 - Six Successive Photographs of the Propagation of Implosion Pressure Waves

The waves are emanating from tiny air bubbles which were attached to a wire. The image frequency is 70,000 per second.

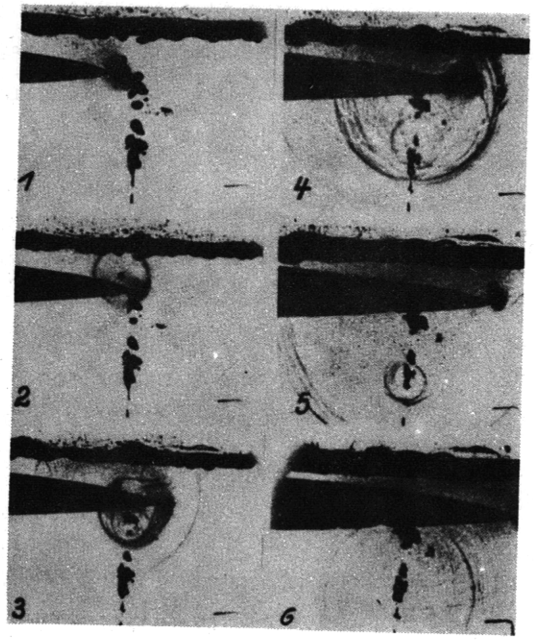

Figure 17 - Implosion of Air Bubbles

The bubbles were fed into water, and increased by a pressure rise caused by the projectile through the liquid. Image frequency 70,000 per second.

This was experimentally proved. Two implosion pressure waves which emanated from small air bubbles present in the water can be recognized in Figure 14. Figure 16 shows the implosions of tiny air bubbles which had attached themselves to a wire.

To check what has just been stated, air bubbles were permitted to escape from a jet placed in the water tank and the bullets were shot through it. Figure 17 shows the pressure waves which emanate from the bubbles.

It must be mentioned that the exposures were made without any special arrangement for streak photography. The pressure rise in the front of the wave must, therefore, be very considerable.

The proof of the existence of these implosion pressure waves is of great importance for the theory of the erosive phenomena in normal cavitation, for conditions are similar there. For example, if the pressure in the narrowest cross section of a nozzle is equal to the water vapor pressure, bubbles of water vapor can be produced which increase in size with the increase of the cross section of flow in such a way that the water vapor pressure is maintained. However, this condition is unstable. A slight rise in pressure results in a sudden condensation of vapor bubbles across the whole section. When these little bubbles collapse a water hammer must result. For various reasons the opinion has now been accepted that the pressure waves produced by this impact are to be held chiefly responsible for the strong erosive phenomena in cavitation. The experimental proof here furnished should considerably strengthen this assumption.

PHENOMENA AT THE MUZZLE OF A FIREARM

The conclusion of the film exhibited in Kreuznach was devoted to the reproduction of the phenomena at the muzzle of a firearm. For this purpose several similar phenomena were suitably synchronized to produce a longer strip of film. However, from a scientific viewpoint this portion of the film offered nothing new. Therefore, reference to the current literature is sufficient.

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