23 October 1959, Volume 130, Number 3382 SCIENCE

Study of Fast Events

Very fine time resolution can be obtained with techniques used in research on explosives.

Wendell G. Sykes

During World War II a great deal of research effort went into the development and improvement of weapons in which chemical and nuclear explosives were used. Of necessity, an appreciable part of this effort was devoted to the improvement of techniques for the study of very fast phenomena associated with explosions. Since the war, research on very fast phenomena has continued, with two important changes: workers in this field have greater freedom to publish their techniques (if not always their results), and important nonmilitary research has been done in the fields of nuclear fusion and the properties of materials under extremely high pressures.

Since many of the methods developed for the study of high-speed phenomena are not well known, this article attempts to provide a general summary of these techniques in the hope that they may prove interesting to workers in other fields (*1*).

Nonluminous Subjects

A camera is about the most useful instrument in the study of fast events, and a considerable number of cameras have been developed with very short effective exposure times. Probably the simplest types of high-speed cameras are those capable only of photographing events that are not self-luminous. With this type of event—a projectile in flight, for example—the exposure time can be controlled by the duration of the light source. One convenient light source is an electronic flash tube. Most of the work on such flash tubes has been done by Harold Edgerton of Massachusetts Institute of Technology. Edgerton's latest type will give a flash with a duration as short as 1 microsecond (10^{-6} second) and an effective brightness of 1 million candlepower (*2*). We have used this lamp with an Edgerton, Germeshausen, and Grier stroboscope to obtain multiple-exposure pictures with a Land camera to give immediate data on the velocity of fast-moving objects.

Another light source frequently used in high-speed photography is a spark gap. By proper design, the effective duration of light from a spark gap can be made considerably less than 0.1 microsecond.

A multiframe camera using spark-gap illumination has been described by Fayolle and Naslin (*3*). This camera has a framing rate in excess of 1 million frames per second for a total of 30 frames and is especially useful for schlieren photography. It uses an optical arrangement first proposed by Cranz and Schardin in 1929 (*4*). Figure 1 shows schematic diagrams of the camera. Essentially it consists of 30 cameras which have either a common objective lens or a common concave mirror in their optical system. Each individual lens can see the object only when the particular spark gap focused on it is fired. The framing rate of this camera is controlled by the firing rate of the spark gaps.

Figure 2 shows a series of schlieren pictures of a bullet emerging from a gun barrel, taken with an 18-frame version of the camera. The schlieren technique shows density variations in a gas due to changes in the refractive index of the gas with density. A concave mirror focuses the image of a point source of light on a knife edge which partially intercepts the image. Schlieren photography is used extensively for wind-tunnel studies of models of supersonic missiles and aircraft. In Figure 2, the bullet (seen in outline only) is traveling in a cloud of propellant gas from the muzzle of the gun. By frame No. 13 the bullet has outrun the gas cloud and is making a shock-wave pattern in the undisturbed air.

Recently the cathode-ray tube has been used as a light source, since the tubes that have been developed for projection of television pictures have very high spot intensity and can be supplied with a phosphor having a decay time of only 0.2 to 0.3 microsecond (*5*).

J. S. Courtney-Pratt has described a high-speed micrographic camera with the same general design as that of Fayolle and Naslin. A multisided pyramidal mirror placed close to a microscope objective viewing the subject can be used to reflect images of the subject to a photographic plate.

Each face of the pyramidal mirror can be selected by a different position of the light spot illuminating the subject. An elegant combination can be made by using a cathode-ray tube as the light source, since the whole photographic process can be controlled by electronic circuits capable of deflecting the electron beam in the tube and turning it on and off. For very fast exposures, multiple spark gaps must be used in place of the cathode-ray tube in order to have sufficient light intensity (*6*).

The micrographic camera just described can be easily modified to permit the study of luminous events by the addition of a rotating shutter (*7*).

If a secondary explosive charge can be tolerated in the experiment, an ex-

The author is affiliated with Arthur D. Little, Inc., Cambridge, Mass.

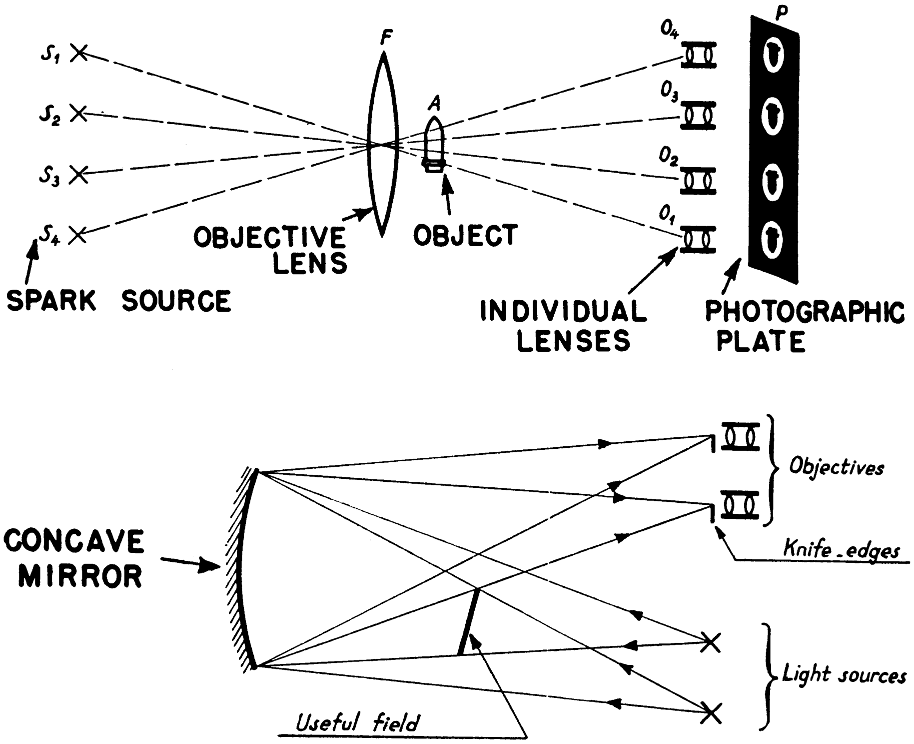
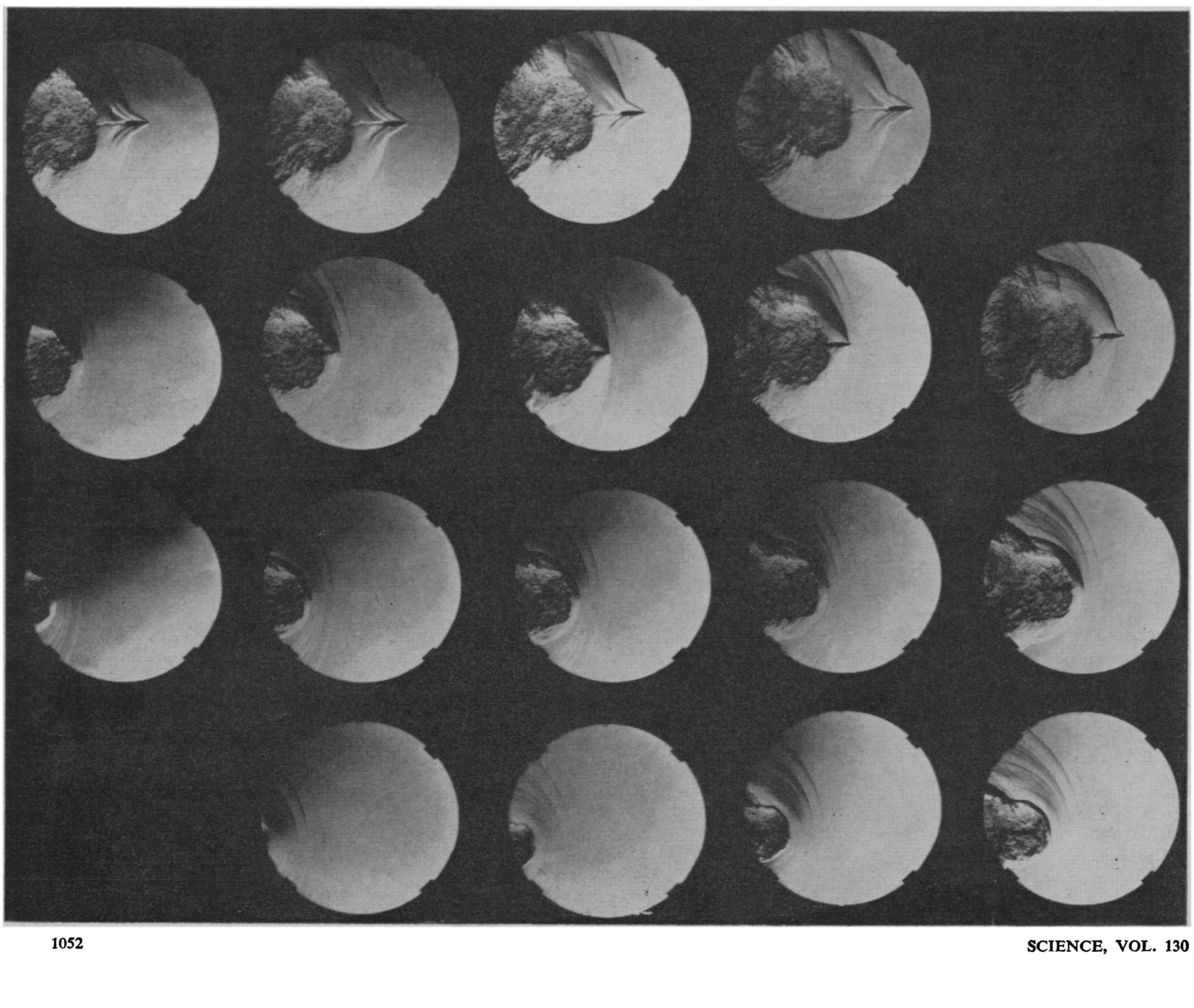


Fig. 1. (Left, top) Simplified schematic diagram of Cranz-Schardin camera. (Left, bottom) Cranz-Schardin camera used for schlieren photography. [From P. Fayolle and P. Naslin, "Simple electronic devices for high-speed photography and cinematography," in *Journal of the Society of Motion Picture and Television Engineers* **60**, 603–626 (1953), and Reprint Volume 5, *High-Speed Photography* (Society of Motion Picture and Television Engineers, 1954), pp. 101–124; courtesy Society of Motion Picture and Television Engineers]

Fig. 2. (Below) Schlieren photograph of a bullet just after it leaves the gun barrel. The framing sequence runs from left to right and from bottom to top. Note the change in parallax from frame to frame. [Courtesy P. Naslin, Laboratoire Central de l'Armement, Paris, France]



tremely intense flash can be obtained from an argon flash charge. When the shock wave from a *brisant* explosive (an explosive having high detonation velocity and power) passes through argon gas near the explosive, a light flash is produced which lasts as long as the shock wave is in the argon. By proper control of the shape and thickness of the argon layer and the shape of the detonation wave in the explosive, the duration of the light pulse can be controlled. Since the shock wave from a *brisant* explosive travels at a high velocity (8 mm/μsec), it is possible to get a flash of very short duration. Bagley has described a small argon flash that can be used in the laboratory with an effective duration of 10^{-8} second (*8*).

On the other hand, if the shock wave can travel a long distance through argon, a "long-peak" flash with a duration of several hundred microseconds can be produced to provide illumination for cameras that use some other method of control of exposure time. At Arthur D. Little we have used a rubber balloon several feet in diameter filled with argon as a long-duration light source. The explosive charge, weighing about ½ to 1 pound, is taped to the side of the balloon away from the event to be studied. The peak brilliance of the argon flash is about 5 to 7 million candlepower per square centimeter (*9*).

Another light source that can be used to provide light of relatively long duration is an exploding wire. A fine silver or copper wire (BS No. 36 to No. 40) will produce a bright flash about 50 to 60 microseconds long when a condenser of 1 microfarad charged to 15,000 volts is discharged through it. The duration and brightness of the flash can be increased by increasing the voltage rating and capacity of the condenser. I have used as much as 4 microfarads and 30 kilovolts, but the cost and volume of the larger condenser bank are such that the results obtained do not justify its use.

Image Compensation

A number of camera types have been described that are not limited to nonluminous subjects. The most widely used type of high-speed camera is actually first cousin to the moving-picture camera. In a moving-picture camera the film moves one frame, the shutter opens and closes, and the film moves again. This type of movement will work up to about 400 frames per second. At a higher framing speed, the film tears because of the high acceleration required. Figure 3 shows a simplified schematic diagram of an "image-compensation" type of high-speed camera which is available in several commercial models. In this type of camera the film moves continuously from the feed spool to the take-up spool. The shuttering action is provided by a glass prism (a

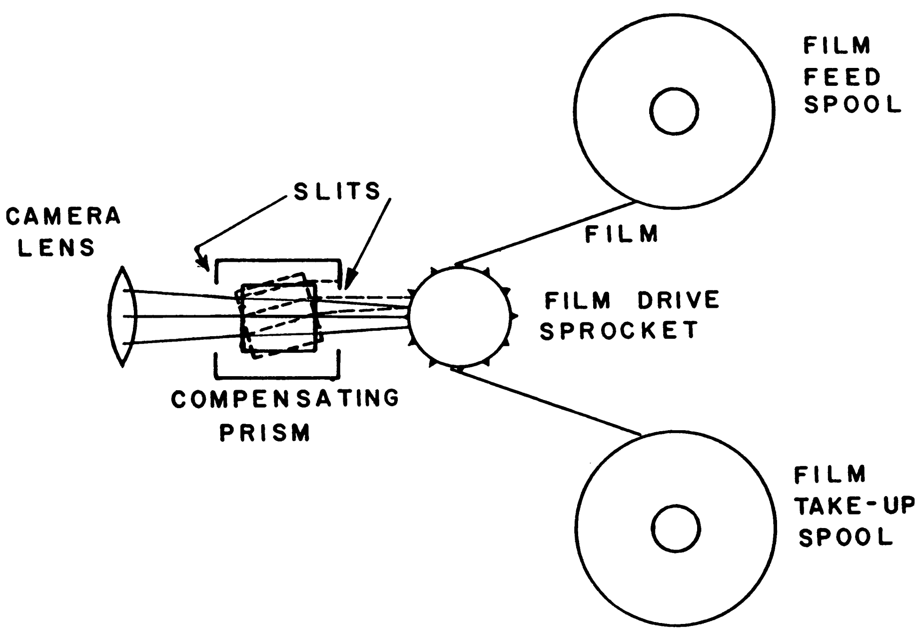


Fig. 3. Schematic diagram of a rotating prism image compensation camera.

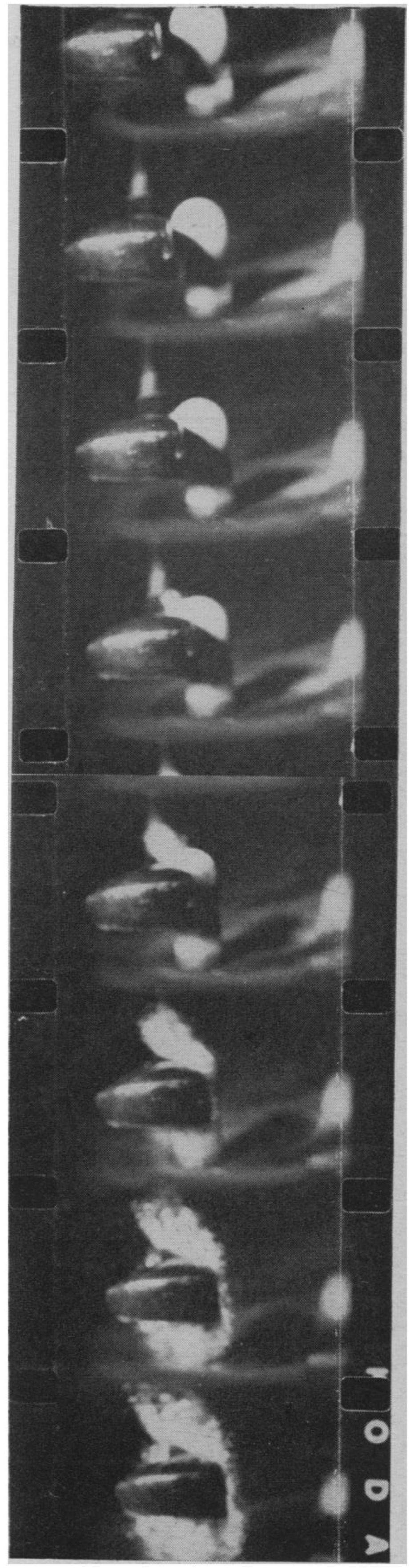
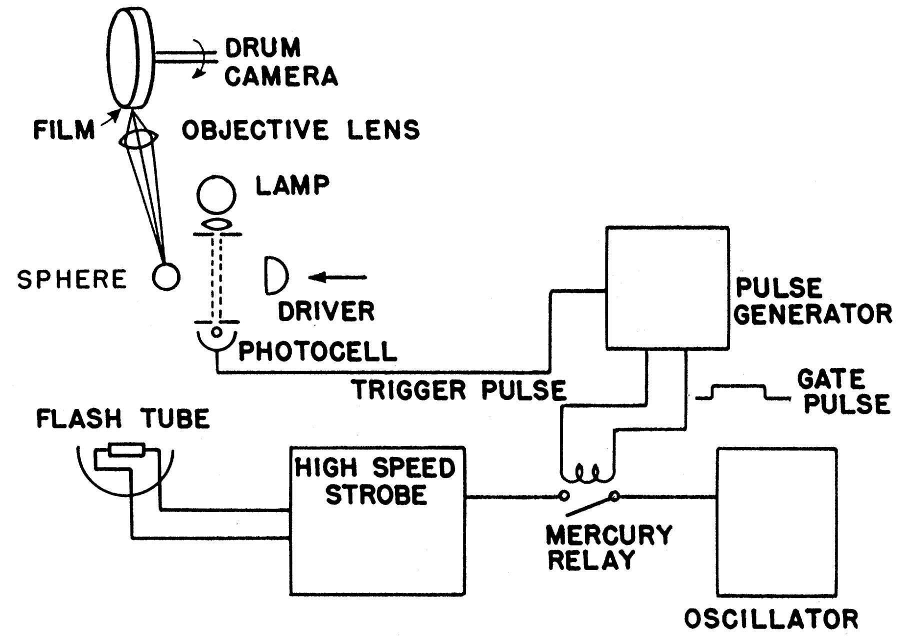
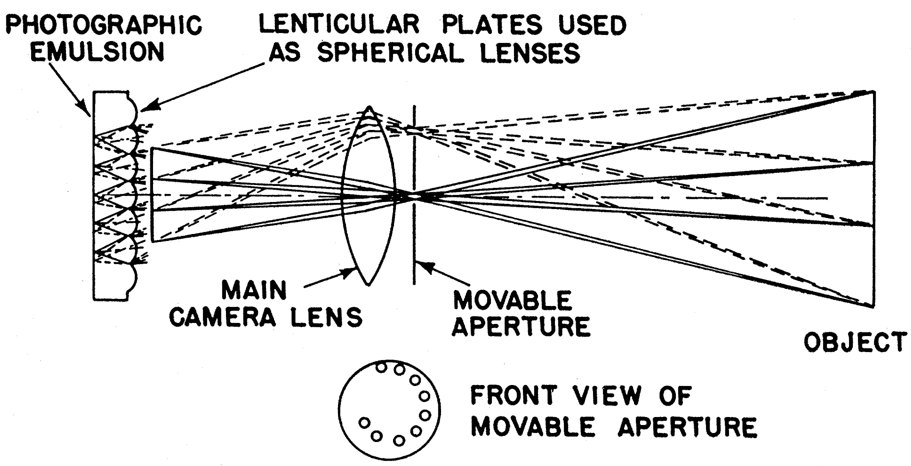


Fig. 4. Club breaking an egg. Framing rate, 6500 frames per second; effective exposure time, 1 microsecond.





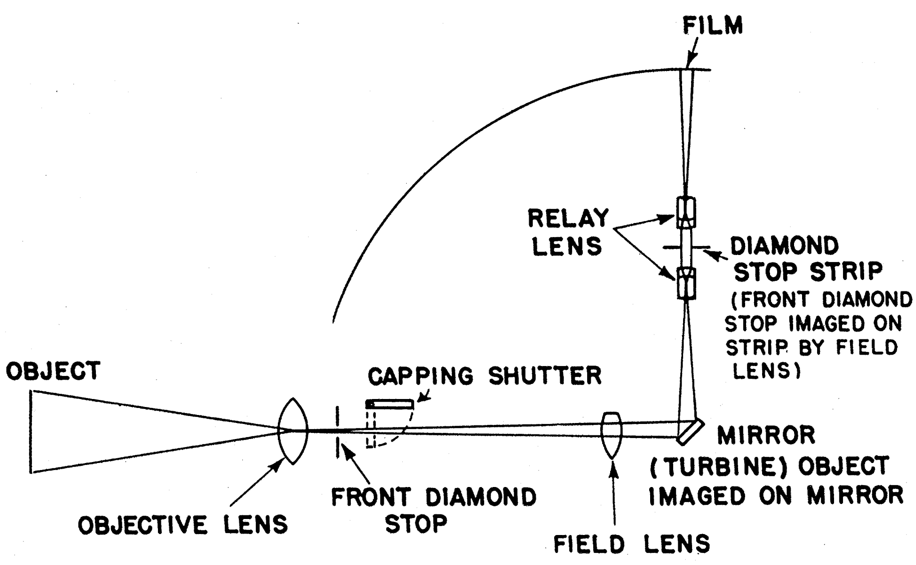


Fig. 5. (Top) Schematic diagram of setup for making high-speed pictures of a driven sphere. Fig. 6. (Middle) Optical system of the image-dissection camera of J. S. Courtney-Pratt. Fig. 7. (Bottom) Schematic diagram of the optical system of the model 189 framing camera. [Beckman and Whitley, Inc.]

cube in this case) geared to the film drive sprocket. By proper choice of prism and gearing, the movement of the image resulting from the refractive effect of the prism can be approximately matched to the movement of the film for about a 20-degree movement of the prism. Shuttering action is provided by slits on either side of the prism. The maximum framing speed of a camera of this type is determined by the bursting strength of the glass prism, the maximum speed at which the film can be driven, and the frame height chosen. The maximum framing rate for a 16-millimeter frame height would be 7500 frames per second, with an exposure time of 30 microseconds per frame. Halving the frame height doubles the speed.

We have done some research on the measurement of the dynamic compressibility of elastic spheres. During this program we made a number of high-speed moving pictures of spheres as they were hit by fast-moving objects. In our early tests we used a Fastax image-compensation camera with the addition of an Edgerton, Germeshausen, and Grier high-speed stroboscopic-flash unit synchronized with the Fastax to shorten the effective exposure time to about 1 microsecond. Figure 4 shows the result when an egg was used while we were testing the apparatus.

For a later series of tests we used an arrangement that gave us much sharper pictures. This arrangement is shown in Fig. 5. Instead of a Fastax we used a rotating drum camera. The framing rate was controlled by the flashing rate of the stroboscope. The stroboscope started flashing when the driver intercepted a light beam near the sphere and stopped after a period slightly less than one drum rotation. The flashing rate was set so that each frame was separated from the preceding one.

Image compensation can also be provided by a rotating mirror, and the film can be transported on a rotating drum. A commercial camera uses this combination to give a framing speed up to 25,000 frames per second for a total of 96 frames.

Image Dissection

Another ingenious type of high-speed camera is based on the principle of image dissection. Close observation of the halftone pictures in this magazine, or any other, will show that they are actually made up of tiny dots, reg-

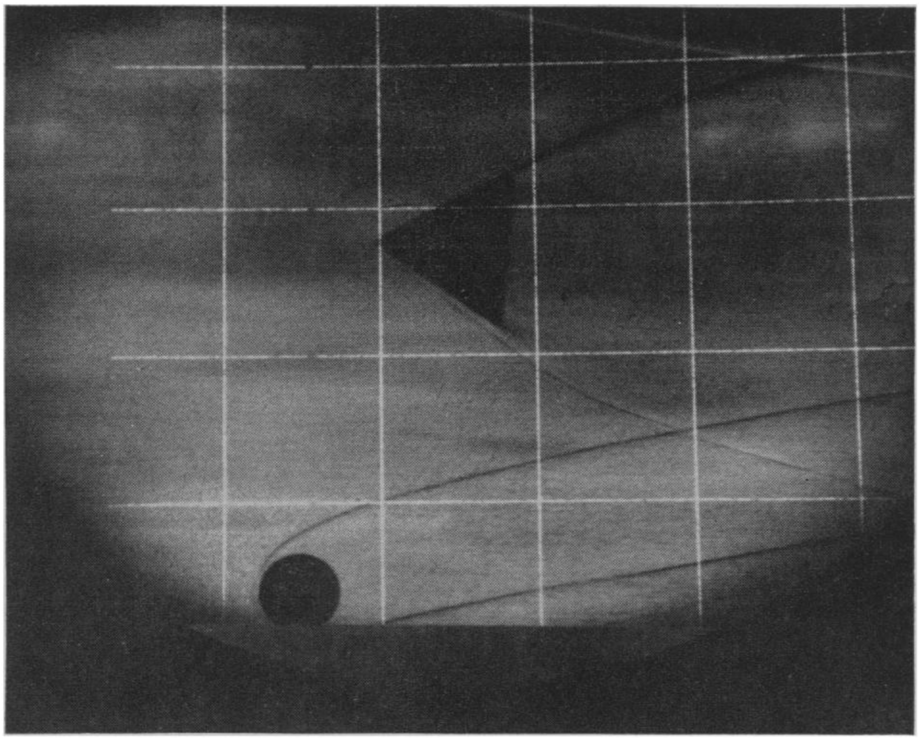


Fig. 8. Air drag measurements in a shock tube. Part of a frame from a series taken by a Beckman and Whitley Model 192 framing camera. The objects (one cone and a sphere) are in free flight at Mach 10.5. Note the shock waves around each object. [Courtesy Gas Dynamics Division, Naval Ordnance Laboratory, White Oak, Md.]

ularly spaced, the darkness of an object being determined by the size of the dots. This suggests the possibility that more than one image could be put on a single photographic plate if dot patterns were placed side by side, since the eye can see a pattern of dots as a picture. Figure 6 shows a diagram of such a camera now commercially available. The image of the object to be photographed is focused by the main camera lens on a special lenticular plate. This plate, made by a firm in Paris, effectively dissects an image falling on it into a series of dots, the position of the dots depending on the direction from which the light falling on the plate is coming. The dots can be spaced as close as 25 dots per centimeter, and the effective diameter of each dot can be made less than 0.02 millimeter (*10*).

The direction of the light in the image falling on the lenticular plate (Fig. 6) is determined by the movable aperture which rotates just in front of the camera lens. In this way, 200 images, each one containing 90,000 dots, can be put on a single photographic plate. The scrambled image can be unscrambled again when the processed plate is put back in the camera with the light behind it, and the camera is used as an enlarger to project each image as the aperture is moved. This camera can take a series of pictures at framing rates as high as 200,000 frames per second.

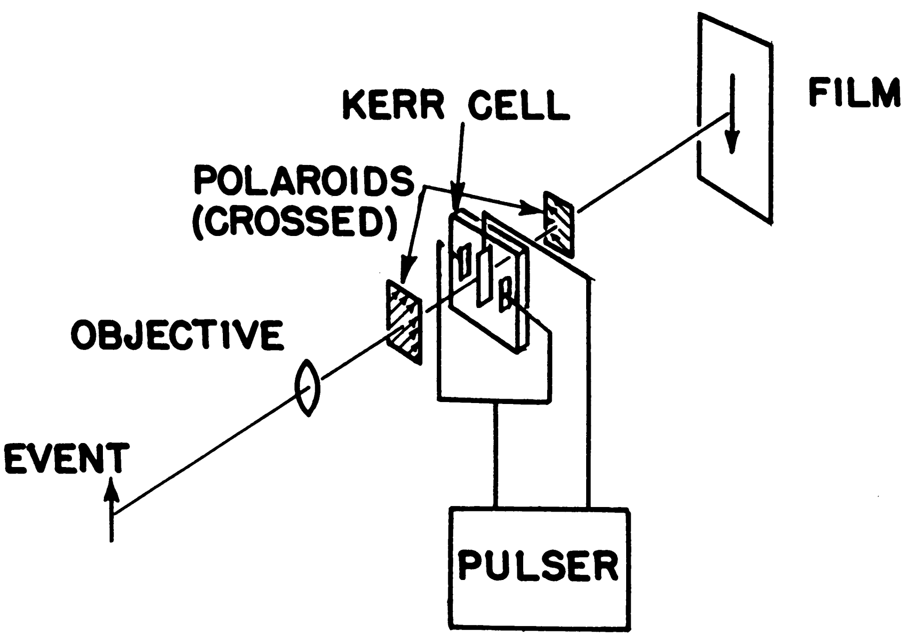


Fig. 9. Schematic diagram of a single exposure Kerr cell camera. Minimum attainable exposure, 5×10^{-9} second.

Framing Camera

Another type of multiple-frame camera that uses mechanical means to achieve very short exposure times is the so-called "framing camera." Designed during World War II for research on explosives, the camera has been improved by a group at Los Alamos under B. Brixner (*11*). Several models of this camera are now in commercial production. As shown schematically in Fig. 7, the object to be photographed is imaged on a very-high-speed rotating mirror (up to 23,000 rev/sec) by an objective and a front field lens. The image on the mirror is then re-imaged on film through a second set of relay lenses. The shuttering action in this camera is provided by the two diamond stops. A fast capping shutter used in this camera consists of an optically flat glass block in the optical system of the camera. A detonator touching one side of the block shatters the block when it is fired, reducing the light sufficiently to prevent fogging of the film until a regular mechanical shutter closes. One model of this camera, built at Los Alamos, has a maximum framing speed of 15×10^6 frames per second for a total of 96 frames. A commercial model of the camera is continuously "open" (that is, it requires no synchronization of the event with the mirror position), costs $80,000, and has recently been advertised as "*the* instrument for the laboratory that has everything."

Figure 8 is part of a frame of a series of pictures taken at the Naval Ordnance Laboratory with a framing camera. In this case, the camera was

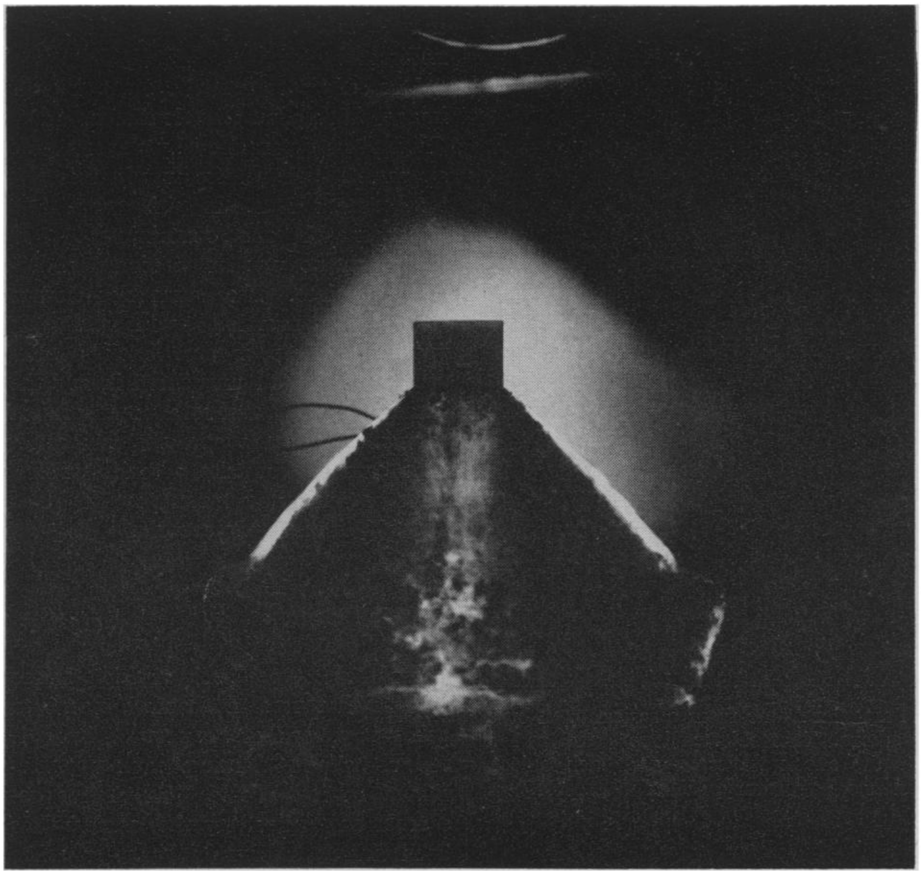


Fig. 10. Detonation of a stick of high explosive. A 35-millimicrosecond Kerr cell shutter photograph of a detonating ¾-inch-square stick of composition B (a military high explosive) that was detonated at the rate of 7.8 millimeters per microsecond. A combination of argon flash front lighting and exploding wire bacz lighting was used. [Courtesy Detonation Physics Branch, Ballistic Research Laboratories, Aberdeen, Md.]

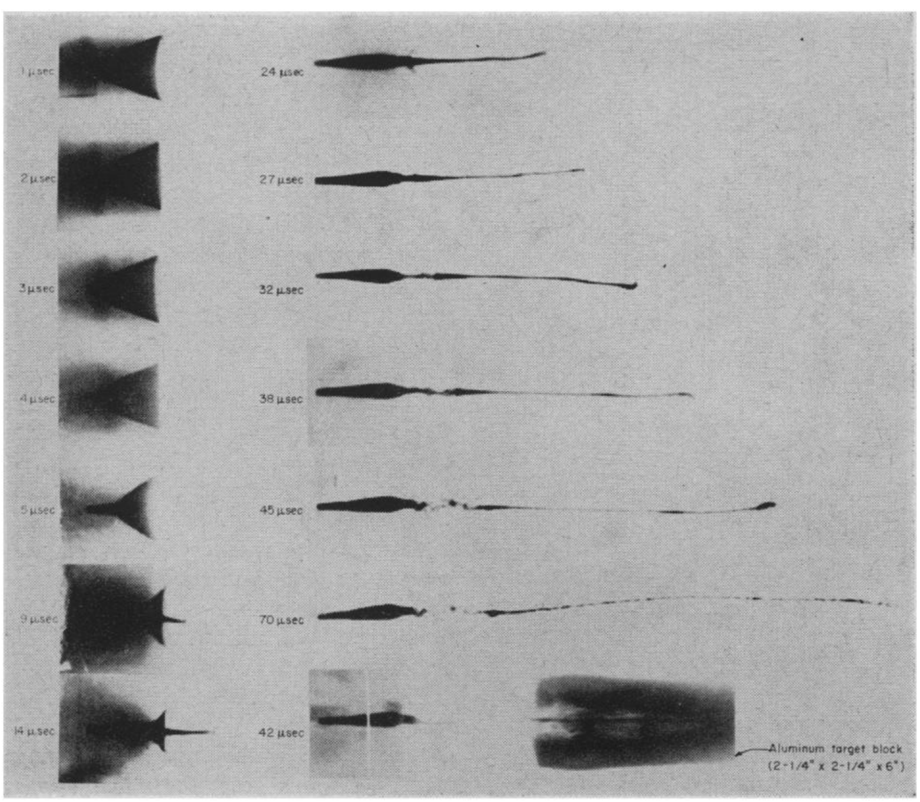


Fig. 11. Flash radiograph of collapsing liners in detonating cavity changes. The liner is 1⅝ inches in diameter and 0.032 inch thick and has a 42° internal angle. The times given beside the pictures are the time intervals after the detonation front reached the base of the cone. Note the considerable internal expansion of the aluminum target block in the last frame. The exposure time for each frame was 0.1 microsecond. [Courtesy Detonation Physics Branch, Ballistic Research Laboratories, Aberdeen, Md.]

used to obtain drag and stability data at very high Mach numbers (Mach 10.5). The objects to be studied were suspended in a shock tube with fine wires, and the flash tube used for lighting was flashed as the shock wave reached them. The duration of the light was electrically controlled to prevent double exposure. A shock tube is a device for obtaining very high pressure pulses and very high gas velocities in the laboratory. High-pressure gas in a chamber is confined by a diaphragm which releases the gas into a connecting tube; a shock wave runs down this tube and can be used in any way desired. The actual drag measurements were obtained from a plot of the position and attitude of the objects under study from frame to frame.

Another type of very fast capping shutter has been described by Edgerton (*12*). A lead grid between two glass plates is fused by a condenser discharge. An optical density of 3 can be produced in about 30 microseconds with this method.

Streak Camera

A specialized camera useful for measuring velocity is the "streak camera." The image of a slit is swept continuously along a strip of film. The resulting picture is a plot of the position of a phenomenon along the slit as a function of time. Although the results obtained are sometimes hard to interpret, a streak camera will give reasonable time resolution without requiring extremely high rotational speeds in the camera mechanism. Streak cameras employing mirrors that do rotate at very high speeds are subject to image distortion due to deformation of the reflecting surface. In some designs the stresses in the mirror are 80 percent of the theoretical breaking stress at top speeds. Brixner has described a method of measuring the surface distortions of the mirror as it rotates so that correcting lenses can be made to compensate for this distortion at several speed increments (*13*).

Shutters

There are two types of fast shutters based on the effect of an electric or magnetic field on the rotation of polarized light passing through a substance. The Kerr cell uses the birefringent liquid nitrobenzene as a shutter. Figure 9 is a schematic diagram of a Kerr cell. A glass cell containing nitrobenzene is placed between crossed Polaroids. When a very strong electrical field is induced between the plates in the cell, the plane of polarization changes and the shutter opens. The open time of the shutter is controlled by the length of the pulse applied to the plates and can be made as short as 5×10^{-9} second (*14*). Figure 10 shows a picture of a stick of detonating explosive taken with a Kerr cell camera at the Ballistic Research Laboratory.

Edgerton (*15*) has used the Faraday effect to make a fast shutter. Like the Kerr cell, the plane of polarization in dense flint glass is rotated by a magnetic field. Due to the inductance of the coil producing the magnetic field, the minimum exposure time of this shutter is about 1 microsecond.

One other type of electrical shutter in use today is based on the "snooperscope" used in World War II. An image converter tube in the snooperscope was used to convert infrared to visible radiation to allow observation of the enemy at night by infrared light. These tubes can be gated on and off by a pulse applied to a grid, and the image can be deflected by a magnetic coil around the tube. Certain types of image converters designed specifically for high-speed photography have been used to give exposure times as short as 1×10^{-9} second (*16*). With the addition of a magnetic deflection system the image converter can be used for multiple-frame photography or as a very fast streak camera (*17*).

X-ray Pictures

High-speed x-ray pictures have been extensively used for the study of explosions where the event of interest is hidden by the reaction products of the explosive. Of course, the x-ray picture is a shadowgraph produced by the illumination from a point source and is limited in resolution by the size of the point source.

Figure 11 shows a series of flash x-ray photographs of the collapse of a cone in a shaped charge, taken at the Ballistic Research Laboratory. The shaped charge was first used in military weapons during World War II, to increase the penetrating power of an explosive warhead when used against armor or reinforced concrete. The shaped charge consists of a hollow metal cone set in the end of a block of explosive. When the block is initiated at the end opposite to the cone, the cone collapses and squirts out a jet of metal traveling about 8 kilometers per second that will make a pencil-sized hole through a thickness of steel about 5 times the cone diameter.

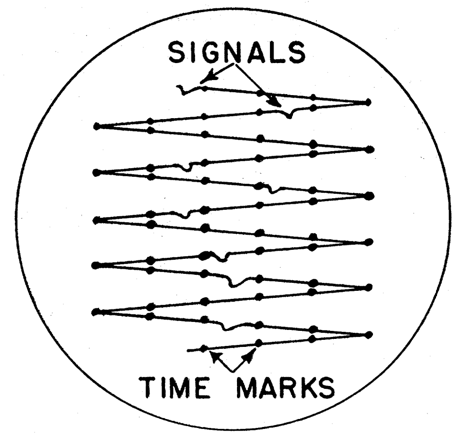


Fig. 13. Oscilloscope trace.

Since the transmission of x-rays through a substance depends on the density of the substance, it is possible to measure the effective density of a compressible substance under dynamic conditions with high-speed x-ray photographs. If density and shock velocity in a material can be measured, the compressibility of an explosively pressurized material can be calculated for a pressure range of 10^4 to 3×10^5 atmospheres (*18*).

Velocity Measurements

The conductivity due to ionization in the detonation zone of an explosive approaches that of a metal. The pressure and temperature involved in the zone are also sufficient to break down insulating materials. This high conductivity can be used to make very accurate measurements of detonation velocity, since a pair of wires through the explosive will be shorted together by the detonation front. Figure 12 is a schematic diagram of an apparatus that we use on a routine basis to obtain detonation velocities. The electronic circuits generate a crystal-controlled triangular sweep on the oscilloscope

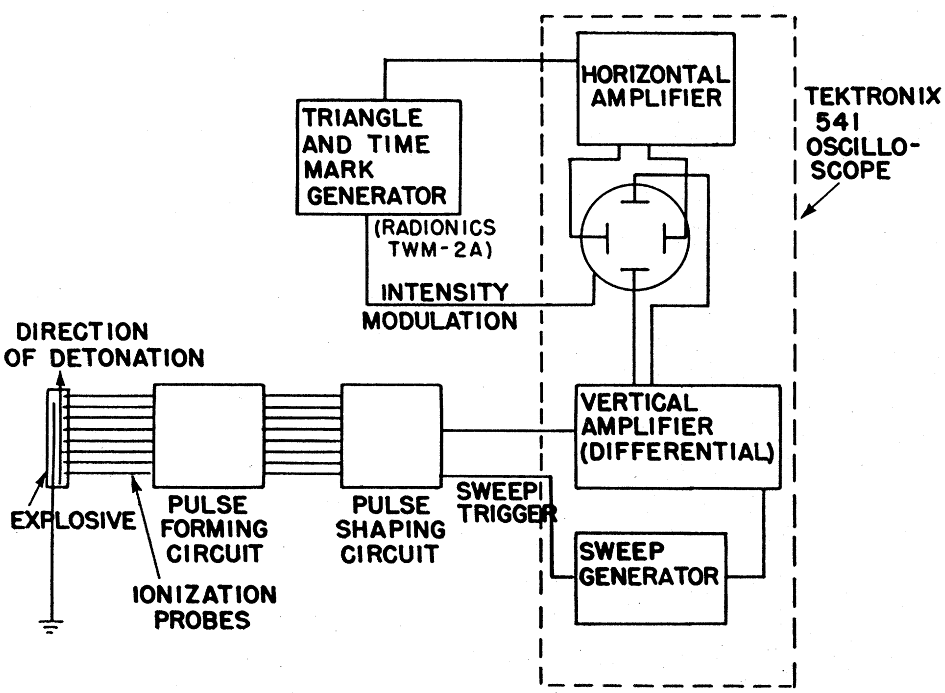


Fig. 12. Portable system for accurate measurement of detonation velocities.

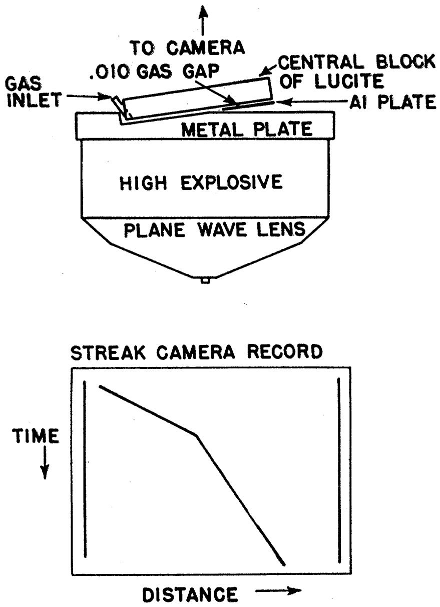


Fig. 14. Experimental setup for measurement of free surface velocity and shock velocity. [From J. M. Walsh and R. H. Christian, "Equation of state of metals from shock wave measurements" (*24*); courtesy the *Physical Review*]

(Fig. 13), with time marks visible as intensity modulation. As each ionization probe is grounded, a pip appears in the trace. This method gives an effective trace length of about 10 feet, enabling us to read time with good accuracy.

It is difficult to generate a triangular sweep with a very fast period, because of the very-high-frequency response required to transmit the sharp ends of the triangle. One solution that has been used is to employ two oscilloscopes with saw-tooth sweeps and common input. One sweep is delayed sufficiently to allow any pip to occur at a point where it can be observed. (*19*).

A method of measuring detonation velocity continuously has been used by several experimenters. Since the conductivity of the detonation front is high, a detonation in a metal-cased charge appears like a piston in a wave guide. The position of the detonation front can be detected by the change in the electrical characteristics of the wave guide at microwave frequencies (*20*).

Physical Measurements

There is another method of obtaining pressure-volume relationships at very high pressures: measuring the internal shock velocity and the free surface velocity of a substance in contact with a block of high explosive initiated in such a way that the detonation front in the block is accurately plane. These shock-velocity measurements have been made in two ways, electronically and optically. The electronic method uses pins set inside the sample and at known distances above it. These pins are short-circuited by the shock wave in the material and by the movement of the free surface (*21*), (*22*).

One optical method is shown in Fig. 14. The position of the internal shock wave and the movement of the free surface are shown by the light from a thin layer of argon behind a lucite block. The shock wave from the metal plate, and from the aluminum plate when it is struck by the metal plate, makes a visible flash in the argon that is recorded by the streak camera.

The break in the streak-camera trace marks the change from the faster shock velocity to the slower free-surface velocity (*22*).

Explosives have been used to induce metallic transitions in insulators. Certain materials like iodine undergo a transition to a metallic state with a low energy requirement (5 electron volts). Explosive pressures of 2.5×10^5 atmospheres have changed the resistivity of these materials from 10^8 ohms to less than 100 ohms (*23*).

References and Notes

1. It is impossible in an article of this length to give credit to all those who have made contributions to the study of high-speed events. The reader who has further interest in the subject will find that the works cited lead to a large number of other references.
2. H. E. Edgerton, "Small zenon flash tube," *Proceedings 3rd Conference on High Speed Photography* (Butterworth, London, 1957), p. 51.
3. P. Fayolle and P. Naslin, "Simple electronic devices for high-speed photography," *High-Speed Photography* (Society of Motion Picture and Television Engineers, 1954), vol. 5.
4. C. Cranz and H. Schardin, *Z. Physik* **56**, 147 (1929).
5. P. Devaux, "Nouveau générateur d'éclairs à tube cathodique et applications," *Actes du 2e congrès international de photographie et cinématographie ultra-rapides* (Dunod, Paris, 1954), p. 43.
6. J. S. Courtney-Pratt and D. P. C. Thackeray, "High-speed silhouette micrography using image-splitting techniques," *Proceedings 3rd Conference on High Speed Photography* (Butterworth, London, 1957), p. 87.
7. J. S. Courtney-Pratt, "High-speed micrography using image-splitting techniques," *ibid.*, p. 81.
8. C. H. Bagley, *Rev. Sci. Instr.* **30**, 103 (1959).
9. C. H. Winning and H. E. Edgerton, "Explosive argon flashlamp," *High-Speed Photography* (Society of Motion Picture and Television Engineers, 1952), vol 5. p. 95.
10. J. S. Courtney-Pratt, "A high-speed cinemicroscope," *Actes du 2e congès de photographie et cinématographie ultra-rapides* (Dunod, Paris, 1954), p. 152.
11. B. Brixner, "A high-speed rotating-mirror frame camera," *High-Speed Photography* (Society of Motion Picture and Television Engineers, 1954), vol. 5, p. 55; "Fifteen million frame per second camera," *Actes du 2e congrès de photographie et cinématographie ultra-rapides* (Dunod, Paris, 1954), p. 108.
12. H. E. Edgerton and F. I. Strabala, *Rev. Sci. Instr.* **27**, 162 (1956).
13. B. Brixner, "Measurement and correction of astigmatic images in rotating-mirror sweeping-image cameras," *Proceedings 3rd Conference on High Speed Photography* (Butterworth, London, 1957), p. 319.
14. A. M. Zarem, F. P. Marshall, S. M. Hauser, *Rev. Sci. Instr.* **29**, 1041 (1958).
15. H. E. Edgerton and K. F. Germeshausen, "A microsecond still camera," *High-Speed Photography* (Society of Motion Picture and Television Engineers, 1954), vol. 5, p. 42.
16. R. F. Saxe, "The short exposure photography of self-luminous events," *Proceedings 3rd Conference on High Speed Photography* (Butterworth, London, 1957).
17. J. S. Courtney-Pratt, "Some new methods of fast photography and their applications to combustion processes," *Fourth Symposium on Combustion* (Williams and Wilkins, Baltimore, Md., 1953), p. 508.
18. R. Schall, "X-ray flash measurements on shock waves in solids," *Proceedings 3rd International Congress on High Speed Photography* (Butterworth, London, 1957), p. 228.
19. A. W. Campbell, M. E. Malin, T. J. Boyd, J. A. Hull, *Rev. Sci. Instr.* **27**, 567 (1956).
20. M. A. Cook, *The Science of High Explosives* (Reinhold, New York, 1958), p. 31; T. J. Boyd and D. Fagan, "A microwave technique for measuring detonation velocity," *2nd ONR Symposium on Detonation, Washington, D.C.* (1955), p. 33.
21. H. D. Mallory, *J. Appl. Phys.* **26**, 555 (1955).
22. Goranson *et al.*, *ibid.* **26**, 1472 (1955).
23. B. J. Alder and R. H. Christian, *Discussions Faraday Soc. No. 22* (1956), p. 44.
24. J. M. Walsh and R. H. Christian, *Phys. Rev.* **97**, 1544 (1955).