High Speed Motion Picture Photography

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A motion picture camera used in taking 4000 pictures per second is described. Applications of high speed motion picture photography to a variety of problems associated with the design of telephone apparatus are given. The resulting pictures in "slow motion" permit convenient and accurate analysis of space-time relationships of mechanical parts in motion otherwise too rapid to be perceived because of their transient nature. This work has related to the development of relays, switches, clutches, ringers, dials, coin collector mechanisms, contact conditions, materials testing, etc. It has been applied to studies of noise reduction in mechanisms and to research problems associated with the production of speech by the vocal cords.

IN 1874 the French astronomer Jenssen pioneered in the use of motion picture photography as a visual aid to the study of a scientific problem. Considerable uncertainty then existed in the value of the earth's distance from the sun and Jenssen employed a camera capable of taking 48 pictures in 70 seconds during the transit of the planet Venus across the sun's disc. He hoped that errors of observation would be substantially less than those inherent in visual observations of this rare and important phenomenon but the results were disappointing due to certain photographic difficulties characteristic of the materials at his disposal. He recognized, however, the value of a series of rapidly taken photographs in making evident to the eye changes in the appearance and position of objects which would not otherwise be perceived because of their transient nature.

E. Muybridge was able to demonstrate in 1878 high speed motion pictures of animals in movement. Jenssen was content to examine his pictures singly under the microscope using the individual photographic images only for record purposes. Muybridge, however, made use of a simple viewing device in which the different pictures secured from a battery of cameras were viewed consecutively when mounted on the inner surface of a rotating cylinder provided with viewing slits. Again we have the application of photography to the discernment of transient movement not otherwise perceptible to the unaided eye. In the following year Muybridge was able to demonstrate the projection of motion pictures onto a viewing screen.

Many workers took up these pioneering experiments and improved devices were developed representing a continuous advance in the motion picture art until today we have a large industry applying the knowledge gathered by these workers to the educational and entertainment field. Paralleling commercial development of the motion picture there has been a continuous advance in its application to scientific and engineering problems, one phase of which relates to high speed motion picture photography.

Amateur and professional motion pictures are taken and projected at the rate of 16 or 24 frames or pictures per second. If pictures are taken at the rate of 48 per second and projected onto a viewing screen at the rate of 24 per second a magnification of the time axis by a factor of two occurs. The visual impression secured will be that of the same occurrence taking twice as long. If 480 pictures are taken per second and projected at the rate of 24 per second, the time magnification is 20. It is this magnification of the time axis which characterizes the picture as a "high speed motion picture." Cameras have been developed which will, under highly specialized conditions, extend the time axis by a factor of 2000 or 3000 times, although such phenomenal speeds of taking impose serious restrictions upon the nature of problems on which they may be used.

Motion pictures are usually made in a camera of the so-called "intermittent" type which refers to an intermittent motion given to the film by the film driving mechanism. An intermittent motion is employed in order that the film may be stationary during the brief exposure portion of the operating cycle after which it is rapidly accelerated and moved to an adjoining section for the next exposure. Mechanical difficulties limit the speed of operation of intermittent film moving mechanisms to a maximum taking rate of approximately 200 pictures per second. High speed motion pictures offering a magnification of the time axis by a factor of 10 can, therefore, be secured with specially constructed intermittent cameras. Higher speeds require the abandonment of the intermittent mechanism and the use of a non-intermittent or continuous film drive mechanism together with means for securing the sharp images required.

If film is moved continuously past an exposure aperture in which lies a stationary image of an object, obviously only streaks will result. Some means must be employed either to illuminate the object brightly for a sufficiently short length of time to avoid blurring of the photographic image or some device must be incorporated in the camera which will cause the image formed by the camera lens to be sharply focused on the film and to move in the direction of film travel with the same velocity. Cameras operating on both principles have been developed and are used in scientific and engineering research. A large part of the work now being done by other workers in this field is with taking speeds extending from a few hundred pictures per second to 2,000 or 2,500 pictures per second.

Cameras of the first type, that is those in which the film is driven continuously and in which the object is brightly illuminated for a short length of time (usually of the order of 2 to 10 microseconds) are relatively simple in construction. Provision is made for the reel of unexposed film which may be 25, 50 or 100 feet in length and have either 16 millimeter or 35 millimeter width. The film may be guided past a fixed exposure aperture or around a rotating drum or toothed sprocket from which it passes to the take-up reel. Power may be supplied through an electric motor either to the take-up reel or to the toothed sprocket. If a stationary exposure aperture is used, two drive sprockets, placed one above and one below the gate, may be employed. Periodic flashing of the illuminant may be secured by the use of a commutator actuated by the camera mechanism.

The second type of camera above referred to employs an optical intermittent to produce the image movement required to avoid blurring when the film is continuously driven past the exposure aperture. A variety of optical intermittents has been developed employing either lenses, mirrors, prisms, or a plane parallel glass plate or block. Regardless of choice of means, the optical intermittent serves to produce a series of rapidly moving images which move with the film velocity. Of these available methods perhaps the simplest is the plane parallel glass plate or block which, by reason of its thickness, deviates or displaces an inclined ray in a manner nearly proportional to rotation about a chosen axis.

At Bell Telephone Laboratories a high speed camera has been developed which normally operates at a taking speed of 4,000 pictures per second. This camera employs optical compensation of the type in which a cube of glass is rotated at a high rate of speed (60,000 r.p.m. for 4,000 pictures per second) between the camera lens and the sprocket as shown in Fig. 1. The compensator cube has four polished faces, each parallel to its axis of rotation and parallel to the axis of the film sprocket. One picture is taken for each quarter revolution of the compensator. The index of refraction of the glass and the dimensions of the cube are chosen to cause correct movement of the image as the film is continuously advanced past the exposure area of the sprocket. The cube rotates in the direction of the arrow which is opposite to that of the sprocket. Downward movement of the image formed by the camera lens results from change in refraction of light rays at opposite faces of the cube as the cube rotates. When the cube is in the position shown at "*A*" an upward displacement of the image to the point "*a*" results. Rotation of the cube in the clockwise direction diminishes the amount of displacement with the result that a downward image movement takes place which is synchronized with

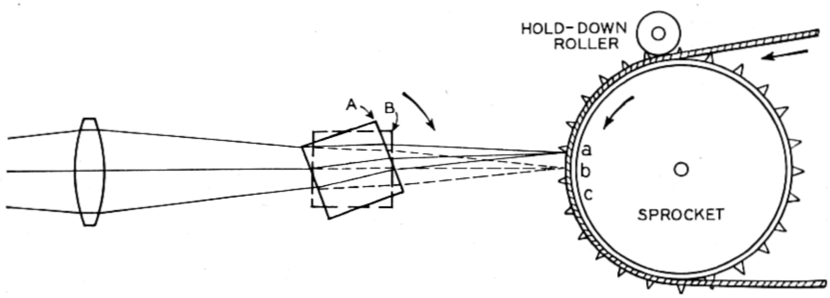


Fig. 1—Schematic arrangement of high speed camera.

the film movement. With the compensator cube in position as shown at "*B*," that is, its entrant and emergent faces perpendicular to the optical axis, no vertical deviation or displacement of the image results and the image falls at the point "*b*" on the film sprocket. Further rotation of the cube causes the image to move downward to the point "*c*" where the exposure is terminated and the next adjacent face of the cube comes into play. In this manner a succession of images is laid down frame by frame at a high rate of speed, each elemental area of the film having received exposure during a substantial part of the rotation cycle. The duration of each exposure is controlled by the film speed and by the angular height of a fixed aperture in front of each of the four faces of the cube. The film sprocket is directly driven from the motor shaft. Spur gears are employed to drive the optical compensator. A separate motor is employed to drive the take-up reel. 16 millimeter film in hundred foot lengths is used.

A finder is provided which permits viewing the image on the film as projected upon a ground glass screen mounted on the hinged door of the camera. Lenses of various focal lengths are interchangeable on the front of the camera. The camera is mounted upon a substantial tripod and is readily portable. Figure 2 shows the exterior of the Bell Telephone Laboratories high speed camera. Figure 3 shows the interior of this camera where the location of the film spools and main drive sprocket are shown. Figure 4 shows the camera with its two motors and portable lighting units of the type developed for

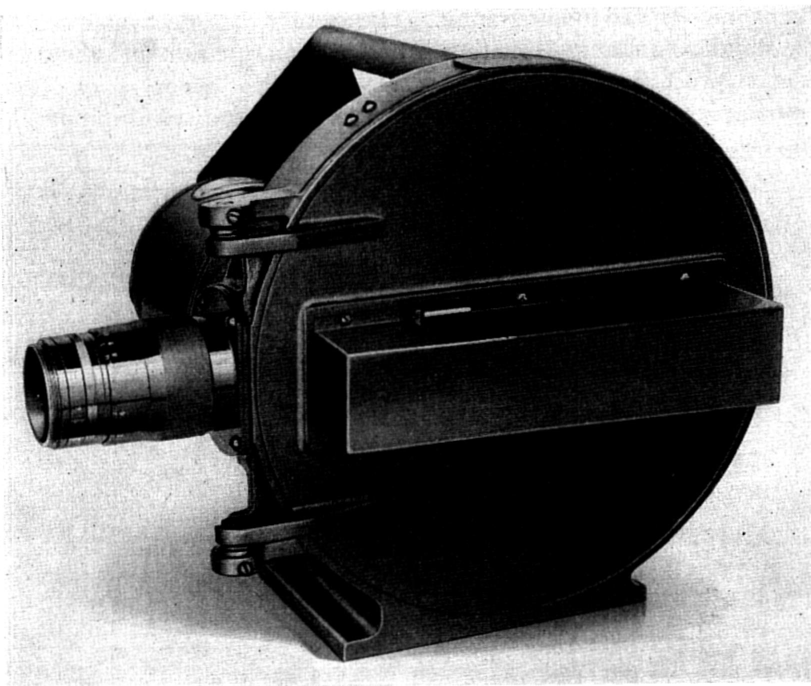


Fig. 2—High speed camera used in taking 4000 pictures per second.

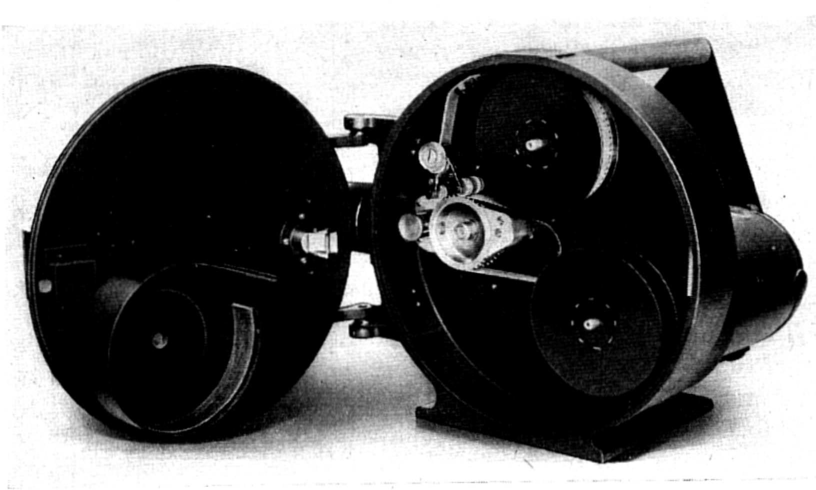


Fig. 3—Interior view of camera.

use in high speed photography. The camera has been adapted to use standard amateur 16 millimeter motion picture film and the commercial processing service of the film supplier is used. High-speed motion pictures in color are readily made, utilizing available films and processing.

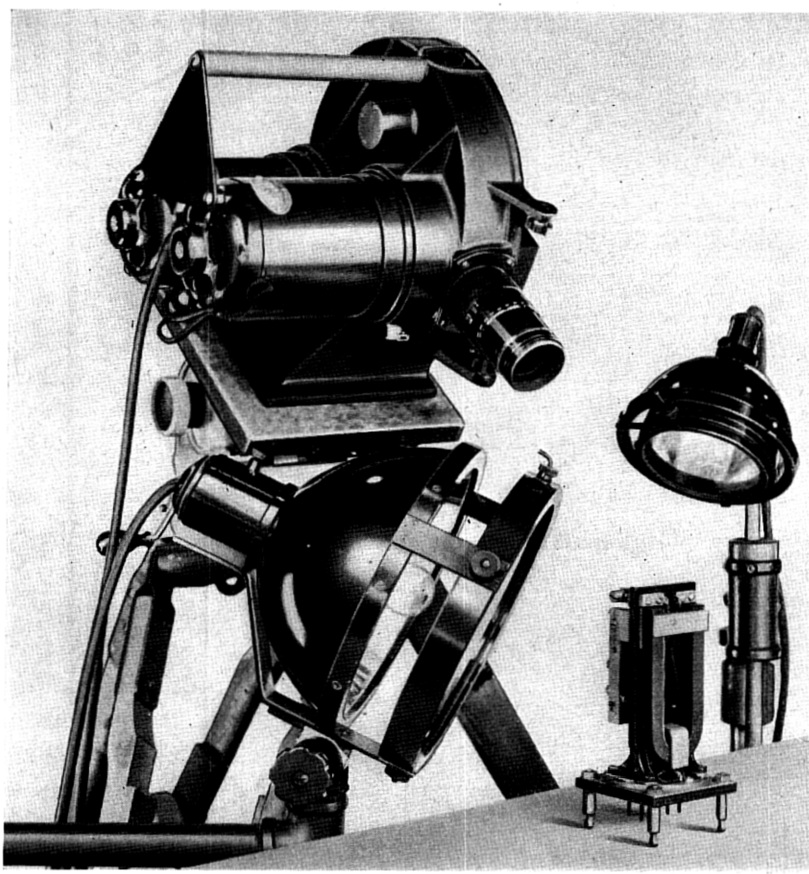


Fig. 4—Camera with portable lighting units used for high speed work.

The optical intermittent type of camera has certain advantages over other types. The unit is self-contained and is independent of lighting equipment. It can be made relatively light in weight and highly portable. Further, it can be applied to the study of self-luminous sources as required in the study of arc lamps, lamp burnouts, fuse burnouts and other problems where the phenomena under investigation are self-luminous.

High speed motion picture photography is finding extensive application in industry where it is applied to "motion analysis" of a variety of manufacturing operations and to problems associated with the design and performance of machinery. A particular value of this method of motion analysis lies in the convenience and accuracy with which space-time relationships of moving parts can be determined. Individual frames can be enlarged as photographic paper prints or projected onto a lined screen; in either case, the movement of parts can be measured with a high degree of accuracy. Extensive application is made in automotive and aeronautical engineering to the study of problems associated with fuel combustion, vibration in motors, airflow around structures and to propeller design and performance. It is coming into use in the fields of biology and medicine, especially in the study of muscular and nervous reactions. It has been applied to microphotography in the photographing of biological specimens at magnifications of 500 to 700 times at a taking rate of 1000 pictures per second.

In high speed photography one of the principal problems has been the securing of adequate illumination of the subject. Exposure times are of the order of one twenty-thousandth second or less for taking speeds of 4000 frames per second. Artificial illumination must be used and arc lamps and tungsten incandescent lamps are employed. Special projection bulbs are secured which are greatly over-voltaged during the few moments required in the taking of a picture. The lamps are designed for short life and to operate as close to the melting point of tungsten as is practicable. Two lamps are operated in series during setting up and adjustment of the apparatus and full voltage applied to both lamps at the moment of taking by the use of series-parallel switching arrangements. The lamps are housed in specially designed lighting units employing high aperture lenses or mirrors which serve to image the source directly on the object at a desired magnification. Provision is made for the reduction of heat by the use of water cells of suitable thickness. Excessive heat in the image will frequently cause distortion in delicate apparatus which must be avoided. One or more lighting units may be employed depending upon the size of the object being photographed, the taking speed, the lens aperture and the film speed. Brightnesses of the order of 10,000 to several hundred thousand foot candles are frequently employed.

At Bell Telephone Laboratories, high speed photography has been applied to a wide variety of problems associated with design and performance of telephone apparatus. Pictures have been taken of standard equipment and of experimental equipment in course of development. Much valuable data not otherwise obtainable have been secured regarding functioning of telephone equipment under use conditions. This work has related to relays, switches, clutches, ringers, dials, coin collector mechanisms, contact conditions, etc. It has been applied to the testing of materials in connection with impact testing, stress analysis and bending moment. It has also been applied to reduction of noise in apparatus, particularly in machines of the type widely employed for accounting purposes, coin counting, typewriter mechanisms, and other high speed operating mechanisms where it was desired to analyze and remedy certain noise conditions. It has found particular use in fundamental research associated with the production of speech by the vocal organs. High speed motion pictures have been made of the vocal cords in action employing taking speeds of 4000 frames per second. These pictures are particularly valuable to teachers of speech and music and to the medical profession. Such pictures have, of course, great value to engineers working on problems associated with the transmission of speech over telephone circuits.

A service in high speed photography is available to engineers of the Laboratories as a visual aid to their study of problems associated with the design, manufacture and performance of telephone apparatus. The high degree of portability which has been achieved in both the camera and lighting equipment lends itself well to extensive application of this service to engineers. Figures A to L show series of individual frames illustrating a variety of problems to which this service has been applied.

High speed motion pictures of a variety of subjects have been taken in color. Color pictures have been made of vocal cords and of photo-elastic effects revealed in transparent materials under polarized light. Such pictures are valuable in studying stress and impact conditions as affecting design of equipment. Stereoscopic high speed motion pictures have been made both in color and in black and white.

High speed motion picture photography is finding increased application to a variety of problems associated with the work of the Laboratories. It is believed that more extended applications of its use will follow.

TYPICAL HIGH SPEED MOTION PICTURES

A—High speed photographs of an experimental model of the step-by-step switch showing the wiper rising to the cut-in position and overthrowing on the first contact of its associated bank. Motion pictures of this type disclosed in great detail movements of the wiper involved in the operation of this switch. These movements are so rapid that but little is learned from a visual examination of the switch while in operation. 4000 pictures per second.

B—These pictures show normal action of the vertical pawl in the step-by-step switch. Again, high speed motion pictures show much that cannot be gained from visual examination. In this case, the pictures revealed whether or not the action of the pawl and ratchet was satisfactory under extreme operating conditions. 2000 pictures per second.

C—To study the conditions under which handset breakage might occur, apparatus was developed in which breakage takes place under controlled conditions. High speed photographs revealed distortions in the handset which under certain test conditions resulted in breakage at the moment of impact. Information relating to the structural strength of the handset was secured from measurements made on many individual pictures of this series. The pictures shown illustrate breakage of an experimental 3-piece E type handset after falling from a height of 5 feet and striking a rigid steel bar shown at the bottom of each picture. 4000 pictures per second.

D—Information gained from a study of high speed pictures of the type represented by C resulted in strengthening of the reenforcement of the handle at certain points which reduced the possibility of breakage under normal use conditions. 4000 pictures per second.

E—High speed photography is applied extensively to the study of explosion of gases in motors, to ballistic problems associated with the explosion of gun powder and to other rapid phenomena of a self luminous type. This series of pictures shows the melting and burning of fuse wire under heavy current conditions. 20-ampere fuse wire is shown during burn-out on direct short. The violence and extent of the action are well shown in these pictures. 4000 pictures per second.

F—Certain normally isotropic transparent materials become birefringent when examined in a stressed condition under polarized light. Extended use of this effect is made in the study of stress distributions in engineering structures and in models of mechanical parts. High speed photography is now applied to these photoelastic effects exhibited in a glyptol sample under impact stress condition. This series of pictures shows impact testing of an unnotched glyptol specimen in plane polarized light. 300 pictures per second.

G—Poor contact conditions in relays may give rise to improper circuit operation. High speed motion pictures have been useful in the study of contact chatter in relays and other similar devices. This series of pictures shows normal operation of contacts. 2000 pictures per second.

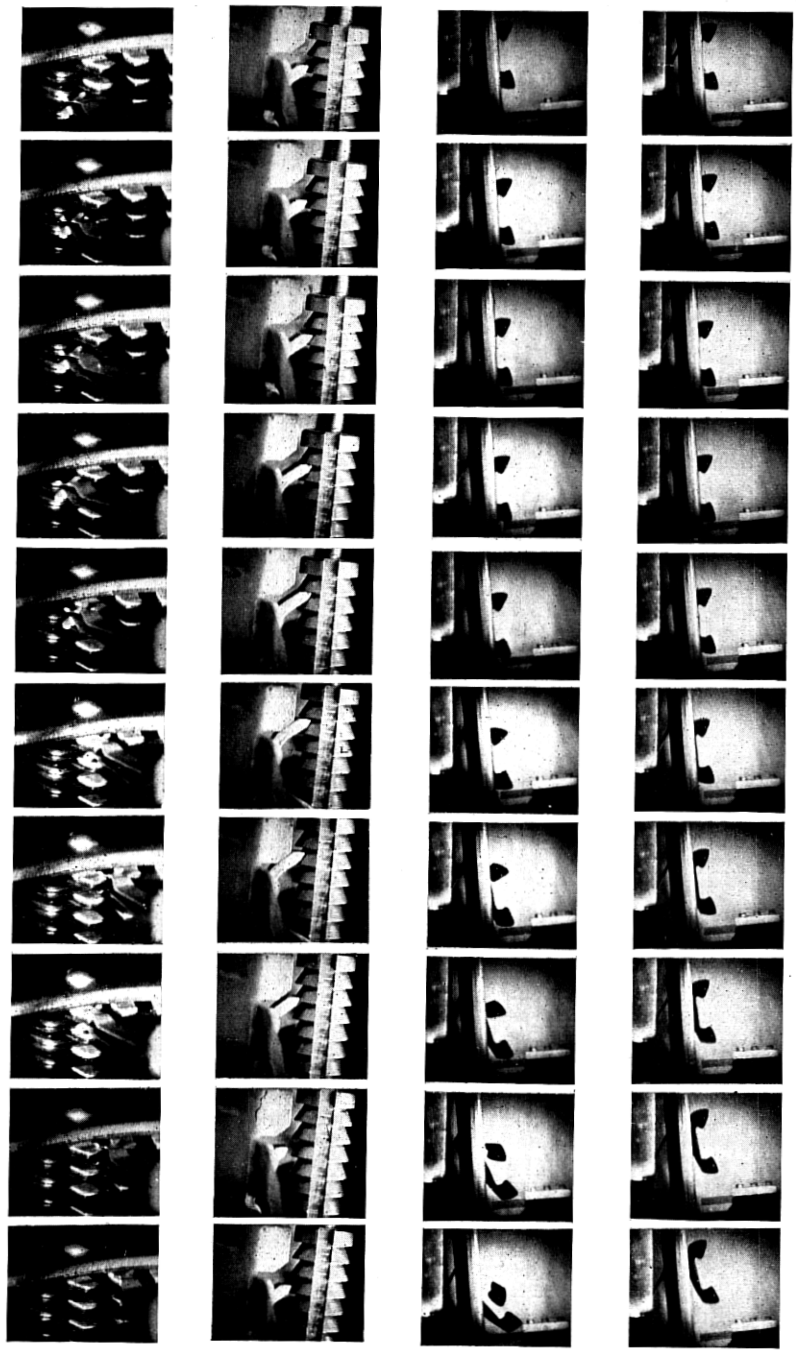
H—This series of pictures exhibits contact chatter. In the first picture of this series the movable contact spring is shown contacting the left fixed contacts. In the second and third pictures, the movable contact spring has been drawn against the right hand fixed contacts. At this point the current is cut off and the movable contact springs return to normal as shown in the sixth picture. Chatter occurs at this point with the movable spring returning to make contact with the stationary contacts shown at the right. Two cycles of chatter condition are shown. 2000 pictures per second.

I—This series of pictures shows the No. 14 teletypewriter locking arm lever and cam during overthrow which gives rise to noisy operation. They illustrate a typical source of objectionable noise in apparatus of this type. Excessive clearance between the cam and the locking arm lever is shown which results in impact noise on the return of the locking arm lever. 1800 pictures per second.

J—This series of pictures shows a modified No. 14 teletypewriter locking arm lever and cam in which the overthrow has been eliminated with subsequent reduction in noise. It can be seen that the lever arm now closely follows the contour of the cam. 1800 pictures per second.

K—A knowledge of the fundamentals of speech and hearing is important to designers of telephone apparatus. High speed motion picture photography has been applied to problems associated with the production of speech by the vocal mechanism. The pictures show vocal cords vibrating in production of speech sound at a frequency of 120 cycles per second. Pictures of this type offer a unique and practical means of securing much useful information relating to the production of speech. 4000 pictures per second.

L—At L is shown the action of the clapper striking one gong of an experimental 20-cycle ringer. This picture revealed more strokes of the clapper per second of operation than was desired. This condition resulted in a peculiar acoustic effect, readily explained from this series of pictures. 2000 pictures per second.



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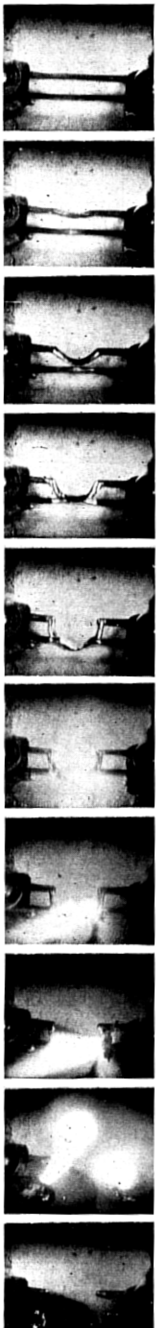

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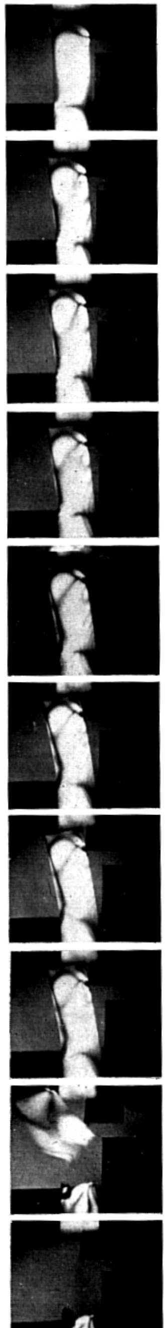

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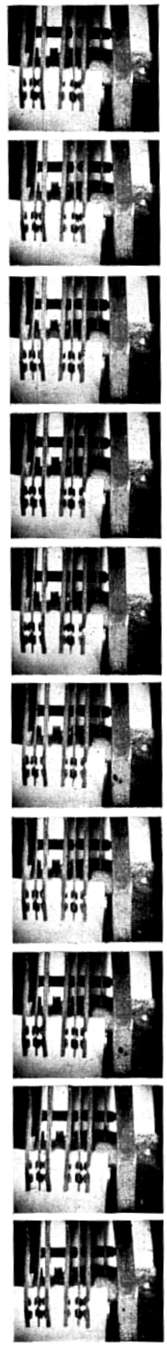

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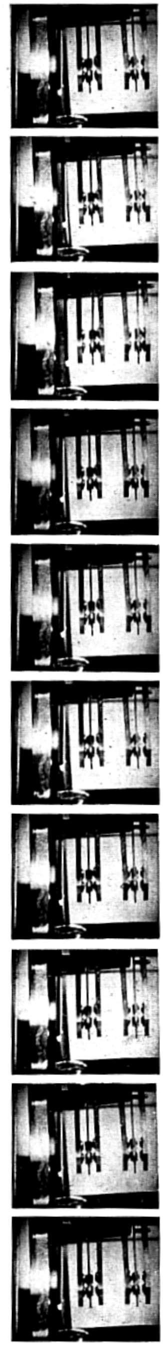

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