

Fig. 7. A multiframe photograph obtained using a multiframe strobe light with a pulse frequency of 120 flashes/s.

For those interested in time-resolved spectroscopy of transient or expanding light sources, a paper presented by W. A. Waller (12) on a new type of framing drum spectrograph should be of some interest. The spectrograph is continuously accessible to the optical event without synchronization. It possesses an additional feature of spatial resolution which is provided by an image trans-

former consisting of an array of 200 μ diameter coated quartz fibers. The fibers are arranged in a 10×10 fiber square (2 mm \times 2 mm) as the entrance aperture of the transformer upon which the light source is focused. In turn, the 100 fibers are arranged in a known order to form a single vertical column of 20-mm high. The end of each fiber acts as a pinhole "slit" which gives rise to an

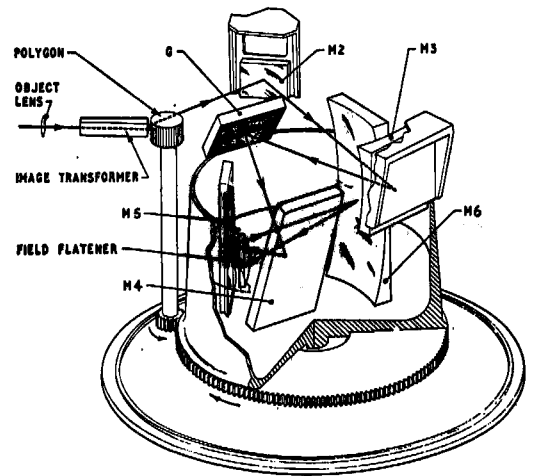


Fig. 8. Optical system of framing spectrograph.

independent spectrum. If all fibers are illuminated by the light source, there will be 100 spectra per frame. A total of 900 frames are recorded in 9 ms at rate of 100,000 frames/s. A rotating polygon positioned in front of the vertical column of fiber ends is geared to the rotating drum of the spectrograph. The polygon contains 90 facet mirrors which provide the framing interval. Figure 8 shows the $f/3$ optical system of the spectrograph. The spectrograph has a wavelength coverage of 3000 to 9000 \AA , wavelength resolution of 5 \AA and a reciprocal linear dispersion of 50 $\text{\AA}/\text{mm}$.

Hypervelocity Impact and the Seventh International Congress on High-Speed Photography

By P. L. CLEMENS

Edit. Note: Papers 41, 42, 43 and 44 from the Seventh International Congress on High-Speed Photography are discussed by P. L. Clemens in relation to the hypervelocity impact aspects, and by J. P. Barbour for the x-ray techniques. In addition, a brief discussion of paper 44 is presented by B. E. Drimmer in his report on shock waves and detonation.

WITH THE ADVENT OF space flight and advanced missilery, studies of the effects of hypervelocity impact have come to be of increasing importance.* Meteoroid collisions with the hulls of spacecraft and warhead encounters with defensive devices may be expected to occur at velocities far exceeding the speed of sound in the structural materials which are involved. (Christman, Gehring, and others have prepared a comprehensive

A paper to be presented during the Society's 99th Conference in Washington, D.C., May 1-6, 1966, by P. L. Clemens, Aeroballistics Branch, Von Karman Gas Dynamics Facility, ARO, Inc., Arnold Air Force Station, Tenn. (This paper was received on March 8, 1966.)

*Numbers in parentheses refer to the papers' numbers in the Congress Program as listed on pp. 353-355. The papers will appear in the *Proceedings of the Seventh International Congress on High-Speed Photography*, to be published by Verlag Dr. Othmar Helwich, D-61, Darmstadt, Hoffmannstr. 59, Germany.

discussion of the basic phenomena of hypervelocity impact.†) At these velocities, analytical methods are often in conflict and of little value in predicting damage effects. Empirical methods must be used to produce data describing the worth of projectile and shielding designs, providing guidance toward design improvements, and furthering understanding of the basic mechanism of hypervelocity impact. In laboratory test work of this kind, projectiles are hurled against specimen targets which are often contained within evacuated chambers. The projectiles are customarily launched either from now-classical, two-stage

†D. R. Christman, J. W. Gehring, C. J. Maiden and A. B. Wenzel, "Study of the phenomena of hypervelocity impact," *General Motors Defense Research Laboratories TR-63-216*, June 1963.

guns‡ or by shaped charge devices. In either case, the gathering of definitive data during the testing relies heavily upon high-speed photography and imposes a challenging set of requirements. The more demanding of these requirements stem chiefly from three characteristics of hypervelocity impact:

(1) Projectile velocities as great as 33,000 ft/s (two-stage guns) or 52,000 ft/s (shaped charge launchers) are encountered. Thus, photographic methods must provide submicrosecond exposure durations to resolve the behavior of small particles effectively.

(2) Clouds of particles are ejected during impact crater formation. These obscure from view many of the effects which occur during critical phases of the

‡W. D. Crozier and W. Hume, "High velocity light gas gun," *Jour. of Applied Physics*, 28: Aug. 1957.

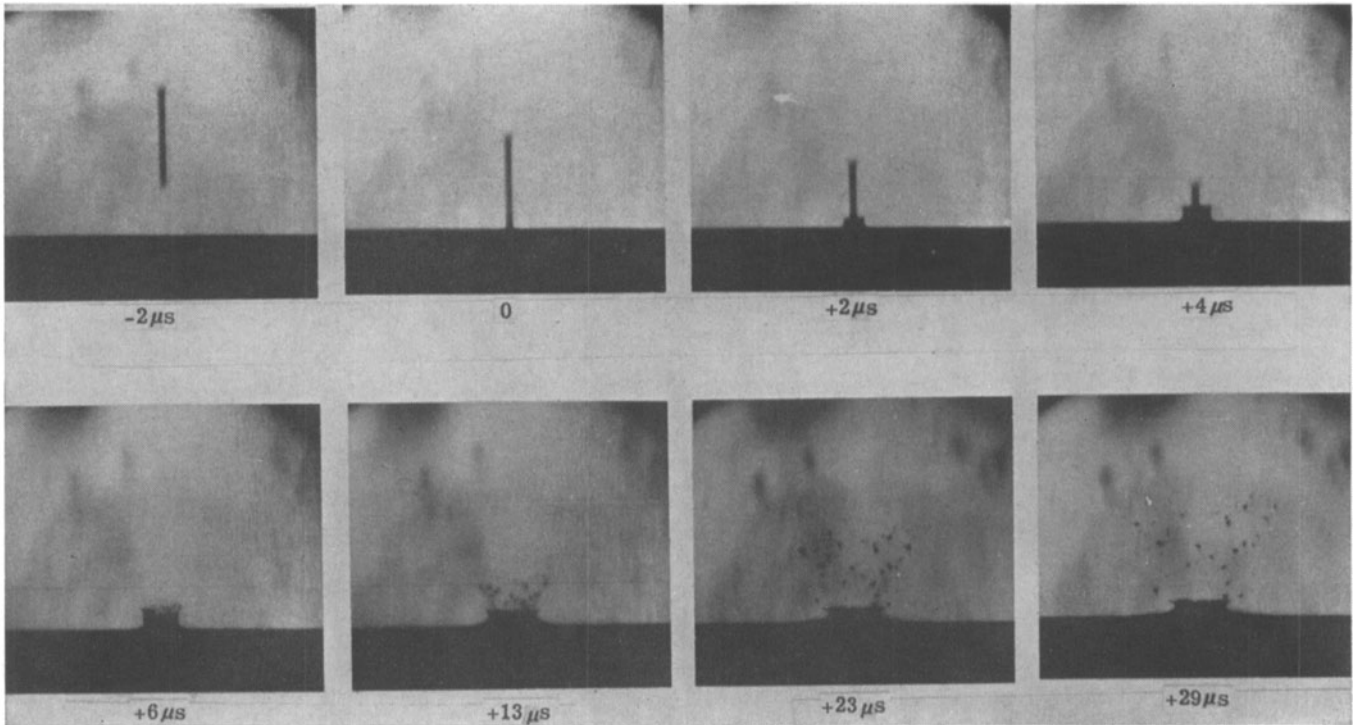


Fig. 1. Framing camera photo sequence showing steel rod impacting aluminum target. Each exposure: 0.1- μ s duration.

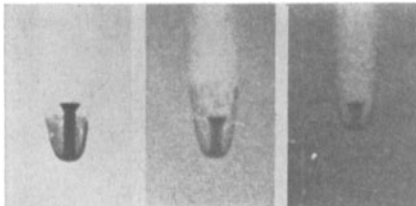


Fig. 2. Use of penetrating flash radiography reveals behavior of projectile within target during high speed impact: left, polyethylene; center, magnesium (A Z31B-F); right, aluminum (2024-T3).

impact process, and target structures themselves obstruct observation of such internal effects as rate of crater growth.

(3) The impact may be brilliantly self-luminous, imposing further require-

ments on the design of photographic diagnostic systems.

A number of papers included in the Seventh International Congress on High-Speed Photography directed attention to new or improved techniques useful in the study of hypervelocity impact effects. In a paper of broad scope (57) Gehring and Christman reviewed the general processes of hypervelocity impact and presented several outstanding examples of the use of diagnostic tools now in service. Figure 1 shows a sequence of framing camera photos of a rod-shaped projectile entering the face of a metal target. Exposure duration for each of these frames was 0.1 μ s. Photos of this kind are now relatively commonplace in the work of the authors, and they portend nothing very spectacular in

themselves. However, when coupled with penetrating flash x-ray films, as reproduced here in Fig. 2, they have enabled the authors to obtain precise data on projectile penetration rates. The paper goes on to tabulate gratifying agreement between measured penetration rate data and corresponding data provided by a particular theoretical approach, viz., the assumption of hydrodynamic behavior and the use of a mathematical model based on incompressible fluid flow.

In the same paper, Gehring and Christman also describe an interesting kind of "pre-impact computer" which clocks the time which elapses while a projectile passes over a measured interval of travel along its trajectory. Then, as the flight continues, the computer digitally

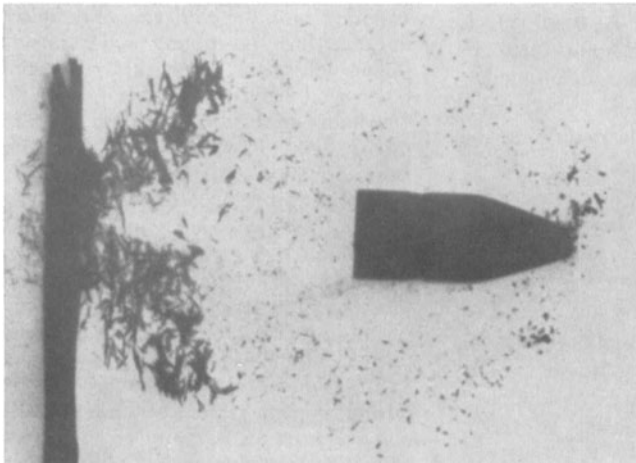


Fig. 3. Betagraph showing 30-06 bullet after penetrating a wood target under vacuum of 0.1 torr; 15-ns exposure on Kodak type R film with bullet 2.5 cm from film and with 45-cm film-to-source distance.

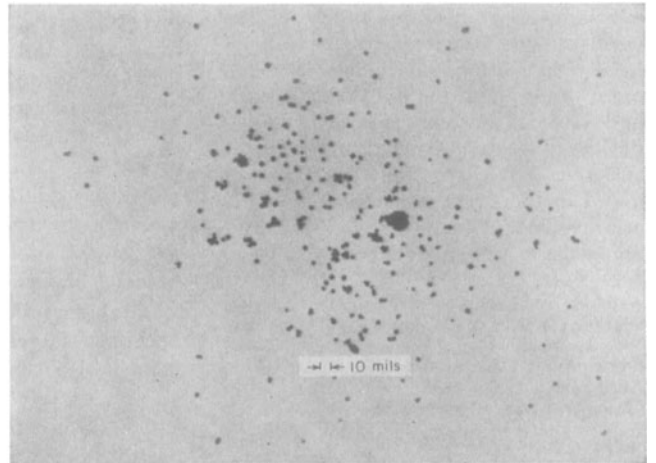


Fig. 4. Betagraph showing 50- to 125-micron glass beads in free fall under vacuum of 0.01 torr. Beads were 2 cm from film; film-to-source distance was 45 cm.

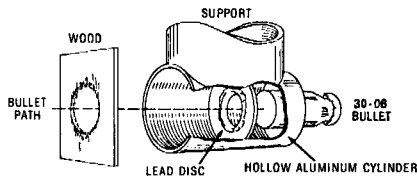


Fig. 5. Object arrangement used in evaluation of simultaneous betagraphy and radiography; 30-06 bullet first penetrated wood plaque, then a lead disc contained inside a hollow aluminum cylinder. Experiment performed at pressure of 0.1 torr.

develops a delayed pulse which may be used to trigger downrange apparatus in accurate anticipation of the arrival of the projectile. Myriad applications will occur to the aeroballistic range technician, and the technique appears to offer extreme accuracy—assuming, of course, that the velocity profile resulting from the projectile drag characteristic is known and properly programed into the system. Since the operation of the device must rely on the successful detection of the arrival of the projectile at each of two stations which bracket the velocity measurement interval, it would seem that accuracy may be gained at the expense of some dependability. The reliability of the system is dependent upon the reliability with which the two detectors can be expected to function sequentially and must be less than the reliability with which either detector might function individually.

A trilogy of papers by Dyke, Grundhauser, Barbour, and others described significant extensions in the state of the art of hypervelocity impact diagnostics. In the first of these papers (41), the seldom-exploited advantages of electron beam photography (betagraphy) are shown. The authors outlined the development of a betagraph device having an effective source size of 1 mm and providing exposure durations on the order of 15 ns. Sample results of the use of the system appear as Figs. 3 and 4. Although velocities here were quite low, the 15-ns exposures would have accommodated far higher speeds with negligible degradation of the resolution which is evident. Using betagraphy to expose film directly, considerably less electron energy is required than is needed to generate sufficient x-ray energy to produce an equivalent exposure. As a result, slower films having greater resolution can be used. The authors report success with the use of thin, opaque, adhesive tapes to exclude light from the film in cases where luminosity of the betographed event might expose the film. (Tape covered the film used in making Figs. 3 and 6.)

Simultaneous use of betagraphy and radiography presents a powerful tool for use in hypervelocity impact diagnostics, as the authors further show.

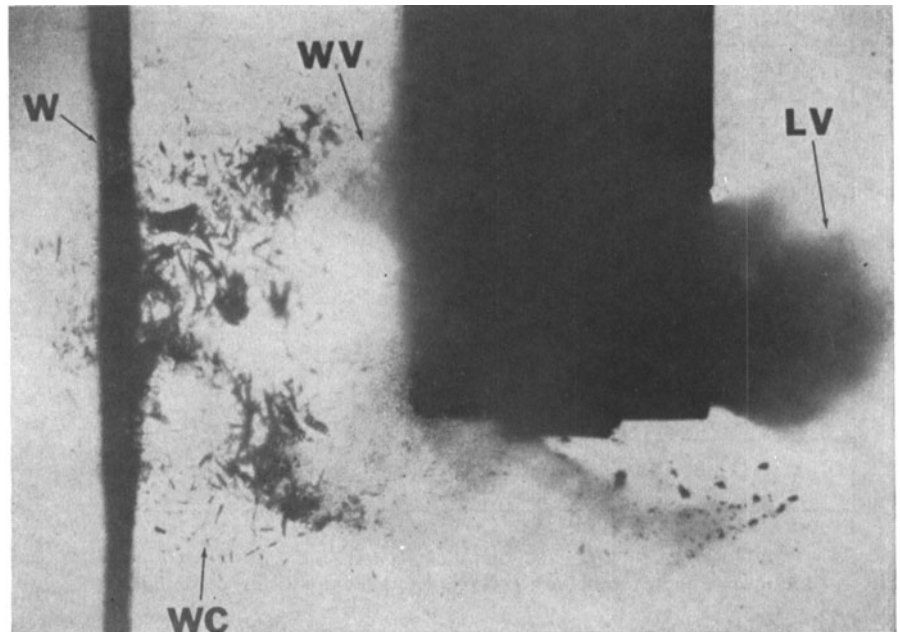


Fig. 6a. Betagraph of event described in Fig. 5. Note wood (W), wood chips (WC), and vapor (WV) caused by impact and vapor (LV), presumably lead, released by projectile impact.

Their development of an especially intense electron beam has made it possible to produce simultaneous betagraph-x-ray exposures from, effectively, a single source. The films to be so exposed overlaid one another, and so parallax is eliminated. Electrons are arrested in the first, slow-emulsion film, where the betagraph exposure is made; x-ray energy passes through the first film layer, exposing it negligibly (because of the low exposure index) and passes on to the second film, where faster emulsion and intensifying screens are found. This simultaneous betagraph and x-ray recording of the same event enables extension of impact observations to a very wide range of object sizes and densities. Figure 5 shows a laboratory setup made to test the efficacy of the system. The results appear in Fig. 6, where surprising clarity of both low and high density particles of widely varying sizes is evident.

In the second of the papers presented by Dyke, et al. (42), a 2 million V x-ray machine is described which overcomes some of the limitations of earlier megavolt machines, notably the relatively long pulse lengths of 150 or more ns and the open construction with the attendant inconvenience of air as insulating medium. This machine enables radiography or betagraphy or both simultaneously, as above. It operates with an electron current of 5000 A and,

§ U. A. Zuckerman and M. A. Manakona, *Proceedings of the 4th International Congress on High-Speed Photography*, 1959.

|| E. W. Walker, "Megavolt flash x-ray equipment," *Proceedings of the 5th International Congress on High-Speed Photography*, 1962, 161.

R. Meakin, "Megavolt flash radiography," *Proceedings of the 6th International Congress on High-Speed Photography*, 1963, 199-204.

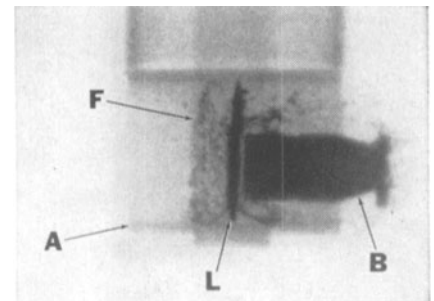


Fig. 6b. Radiograph of same event, made simultaneously with betagraph of Fig. 6a. Note bullet (B), lead disk (L), lead fragments (F), and aluminum cylinder (A).

as an x-ray source, provides a pulse length of 20 ns from a 5-mm source. (X-rays can also be formed at an external target whose expendability enables use of smaller spot size, and greater penetration, than does the internal anode.) Figure 7 shows the exceptional penetrating power of the system and the x-ray shadowgrams which appear as Figs. 8 and 9 display results of its use. From Fig. 8, where film-to-source distance was 45 ft, it appears that particles as small as $\frac{1}{8}$ in. can be imaged. Tube life of more than 350 pulses with no more than one percent variation in x-ray intensity has been verified, and results appear in the paper.

Two related advantages to hypervelocity impact work arise from the intense penetrating power of this system:

(1) Internal structural changes (e.g., rate of projectile penetration and of crater growth) can be examined in impact targets of larger dimensions than previously.

(2) Impact targets of dimensions now current can be examined using greater

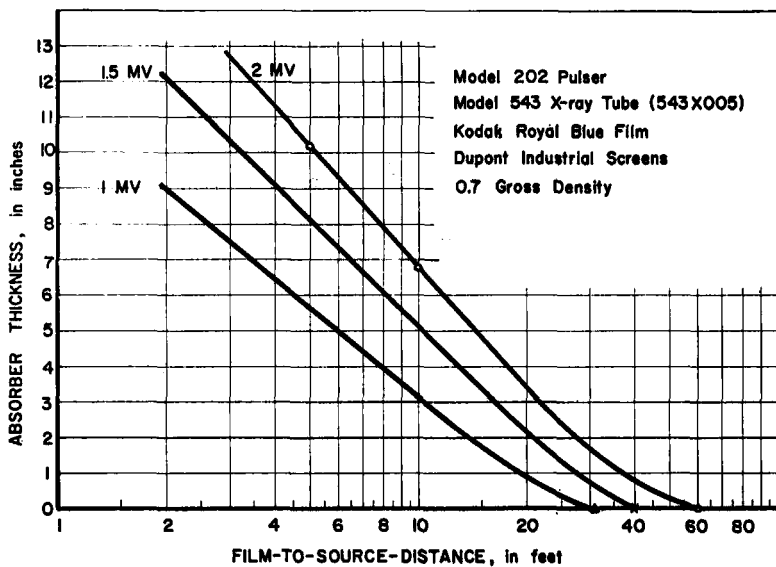


Fig. 7. Aluminum penetration characteristics for three operating potentials.

film-to-source distances and "slower" photographic emulsions, thereby enabling improved resolution.

As a result of the first of these advantages, dispersion of impact projectiles upon launching becomes less a nuisance since larger splatter patterns are accommodated by larger targets. As a result of the second, subtle structural changes which went unnoticed in the past can now be brought under scrutiny.

In their final paper, authors Barbour, Grundhauser, and Dyke describe a new system of cineradiography which employs a single, field emission x-ray source and is capable of repetition rates as high as $10^6/s$ (43). This is made possible by the development of a novel field emission diode rectifier which will pass currents as great as 2000 A in the forward direction but which can withstand inverse voltages of 150 kV without conducting. Thus, the energy stored in each one of a group of pulser power

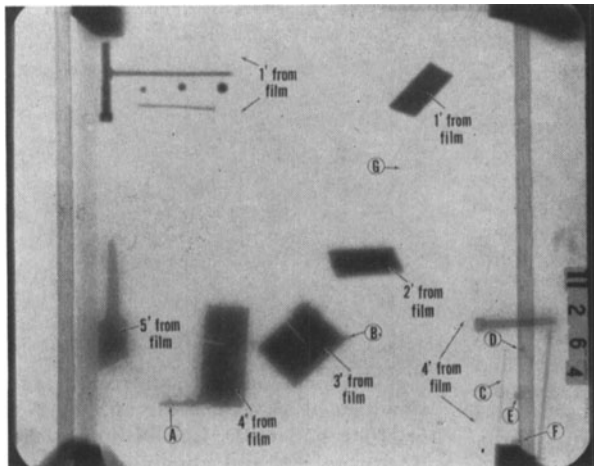


Fig. 8. Shadowgraph of objects lying at distances from film plane as noted. Film-to-source distance: 45 ft. Background film density was 1.5.

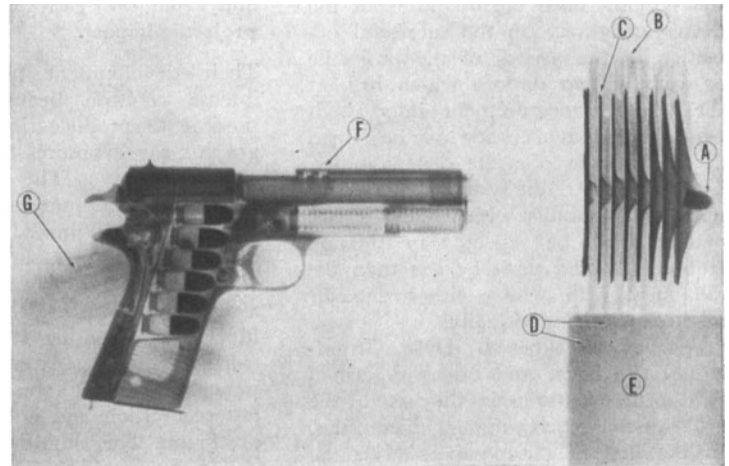


Fig. 9. Radiograph of bullet (A) from Colt automatic pistol fired into lead (C) and wood (B) laminated target. Hand (G) holding pistol can be seen.

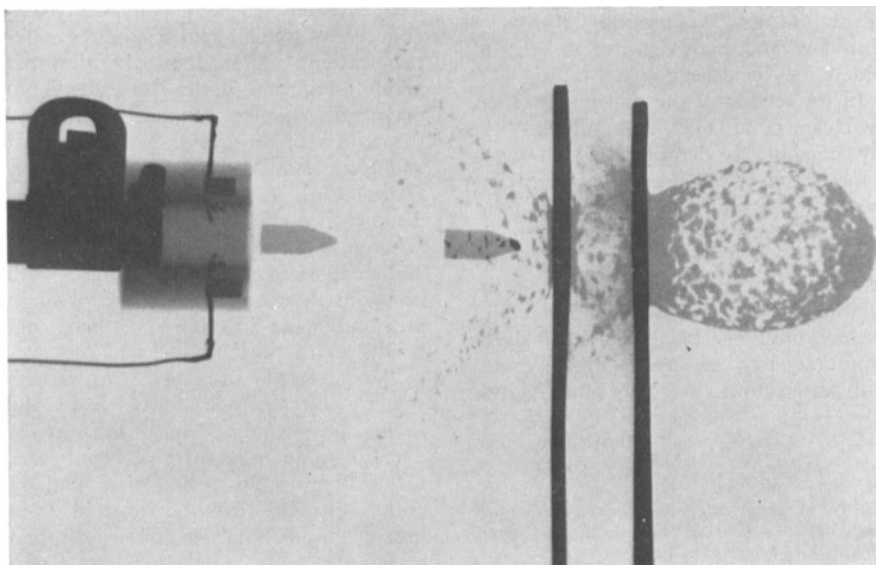


Fig. 10. Three-exposure cineradiograph of 30-06 bullet in air (two exposures) then penetrating two lead plates. Exposure durations: 70 ns.

supplies can be discharged through a diode and through a single, common x-ray tube but not through the other pulsers. Triggering of these controlling diodes to discharge their respective power supplies in rapid sequence produces the desired x-ray pulse train. It is to be noted that multiple x-ray sources have been used in cineradiography for some time^{†, **}. At the present state of the art, these multiple tube systems give frame rates exceeding $10^6/s$, and these are the highest attainable. However, in many hypervelocity experiments a single source is preferable in order to eliminate parallax, making it easier to separate source and object motions. Single-source x-ray tubes having heated cathodes have been used at low frame

[†] F. J. Grundhauser, W. P. Dyke and S. D. Bennett, "A fifty-millimicrosecond flash x-ray system for high-speed radiography," *Jour. SMPTE* 70: 435-439, June 1961.

^{**} Encyclopedia of X-Rays and Gamma Rays, Reinhold, 1963, 1097-1098.

rates in medical cineradiography,†† and in other research as higher frame rates.‡‡ However, the system described in this paper overcomes the disadvantages of inadequate penetration and lengthy exposure duration which were found in earlier systems; hence, it is better suited to hypervelocity impact work. Figure 10 shows a triple exposure made with the system.

During the Sixth International Congress on High-Speed Photography, Koch and Simon reported on a multi-station shadowgraph system featuring a novel method of projectile detection and shadowgraph triggering§§ which may be useful in some hypervelocity impact work. That same system, now refined and extended, was described again in the Seventh Congress (31). The detection scheme makes use of a microwave Doppler radar arrangement, whose

†† Greenwood, et al., Crichlow, et al., Astley, et al., *Brit. Jour. Rad.*, 29: 1956, 556.

‡‡ L. C. Foster and J. K. Landre, *Electro Technology*, Feb. 1962, 197-198.

§§ B. Koch and G. Simon, "Synchronization of ballistic time-sequence picture photography by R.F. velocity measurement techniques," *Proceedings of the 6th International Congress on High-Speed Photography*, 1963, 409-412.

output is supplied to a frequency divider from which the shadowgraph trigger pulses are developed. Trigger pulses are produced, thereby, at projectile positions along the trajectory which are separated precisely by integral multiple microwave half-wavelengths. The authors report relative scatter in velocity measurements of the order of only 5×10^{-4} . Unlike the Gehring and Christman "pre-impact computer" already discussed, this system can be relied upon to develop trigger pulses upon projectile arrival at various stations along its trajectory quite regardless of any drag-induced decay in velocity. This system is, however, considerably more complex than the one which was described by Gehring and Christman.

Some of the problems found in the photography of exploding wires are similar to those which arise in the recording of hypervelocity impact phenomena. Time scales are similar; the exploding wire is enveloped in an opaque, luminous sheath; and there is need to image minute particles. Chace, Levine and Fish reported an x-ray technique used in the study of exploding wires (44), and the results are encouraging

to those who use radiography in impact diagnostics. Working with a flash x-ray system having an exposure duration of 30 ns, the authors compared radiographic images of exploding wire phenomena with back-lighted photographs made using visible light (from an exploding metal foil) and a Faraday shutter camera. It is readily seen from the comparisons that the x-ray technique records the cloud of exploding wire material while the photography records a misleading larger and earlier luminous shroud. Neither the form nor the dimensions of the cloud of wire material are interpretable photographically.

As is quite evident, a generous sampling of the papers presented before the delegates to the Seventh International Congress on High-Speed Photography bore, either directly or indirectly, on hypervelocity impact diagnostic techniques. Some of these techniques were developed independently of an immediate need for their application to specific investigations; others were born out of pressing necessity. High-speed impact research continues to stand as a demanding benefactor of the art of high-speed photography.

Summary of Papers Dealing With X-Ray Techniques

By J. P. BARBOUR

FLASH x-ray technology has advanced rapidly in recent years, and now makes a significant contribution to the field of high-speed photography. One session at the 7th International Congress on High-Speed Photography was devoted entirely to x-rays, and the present text reviews the papers delivered during that session.

X-rays penetrate matter and, because of differential absorption, information about the thickness, density or type of material is carried by the transmitted beam. In many cases radiographs yield data which cannot be obtained with light because the subject may be totally obscured by an opaque medium, or self-luminosity of the surroundings may preclude direct visual or photographic observation. X-rays also yield data on density variations in opaque media, such as those caused by shock waves, voids or variations in thickness.

The papers presented at Zurich

A paper to be presented during the Society's 99th Conference in Washington, D.C., May 1-6, 1966, by J. P. Barbour, Field Emission Corp., Melrose Ave. at Linke St., McMinnville, Ore. 97128. (This paper was received on March 8, 1966.)

covered a wide range of applications such as the study of exploding wires (44),* industrial development (45), and medical research (37). The new equipment described included a 2 million-volt generator (42), a high-speed cineradiography system (43), and an electron beam source with which pictures can be obtained simultaneously with x-rays and a pulsed electron beam (41).

Flash X-Ray Discharge Mechanisms

The discharge mechanism in low voltage flash x-ray tubes was investigated by Händel and Bergfeldt (40). A coaxial system was constructed in which a high-voltage capacitor was discharged through a diode flash x-ray tube. The voltage, current, time derivative of the current and the x-ray output were all measured. The experimental results were in accordance with Händel's theory which postulates that a pinch effect in the flash x-ray discharge causes

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a voltage increase across the tube electrodes.

The experimental apparatus is shown in Fig. 1. The high-voltage capacitor was charged and the spark gap was then triggered in order to apply the voltage to the tube anode. The pickup coil for measuring di/dt is positioned near the anode, and the cathode has an aperture through which x-rays are transmitted to the detecting instruments. The system is completely coaxial to minimize circuit inductance.

The tube voltage is assumed to be given by the equation

$$V = [R + (dL/dt)]I + L(di/dt) \quad (1)$$

where R is the resistance and L the inductance of the discharge tube. I and V were measured directly and values of R and L could be determined from the data. A schematic diagram of the equipment is shown in Fig. 2. The time derivative of the tube current was measured with a pickup loop, and the current waveshape was obtained by applying a portion of this signal to an integrating network. Typical waveforms are shown in Figs. 3 and 4. In addition, Fig. 4 shows the values of R