

Shock Waves and Detonations

By B. E. DRIMMER

THE 7th International Congress on High-Speed Photography contained, as did its predecessors, many papers of interest to scientists whose fields lie outside photography. The highlights and short summaries of papers having a direct impact on the area of detonations and shock-waves are presented. Most of the technical material has been omitted, but enough has been included to interest experimentalists in these areas so they will read the *Congress Proceedings* for details.*

The initiation of detonation in liquid explosives is receiving increasing detailed study both here and abroad.† M. P. McOnie (22) showed some excellent pictures of the build-up to detonation of a 0.1-mm thick film of nitroglycerin, initiated by an electric spark. Figure 1 shows the experimental arrangement used, and Fig. 2 shows a typical set of results obtained with an A.W.R.E. C4 continuous-access camera.‡ (This camera has the capability of taking up to 140 photographs at a framing interval of 5 μ s and a frame exposure time of 1.3 μ s). Using transmitted light from a xenon-filled flashtube, the photographs show some of the details of the complex interactions between bubbles and cavities, subsonic burning in the liquid, and pressure waves that finally result in transition to explosion. Such clear photographs are of great help in developing deeper understanding of the critical role played by bubbles and cavities in this incompletely understood phenomenon.

The "art" of explosive forming of metal plates is being placed on a firmer scientific base by the careful work reported by R. E. van Wely and J. D. van Leeuwen (23). They discussed, among other things, their stereoscopic technique in the arrangement shown in Fig. 3, wherein a grid on the back side of the 1.5-mm thick, 20-cm diameter mild steel plate was photographed. The light for the Dynafax camera photographs was

sent to the plate, and reflected back via a hole in the die. As the plate, impelled by the detonation of 20–30 grams of sheet explosive placed in the water above the plate (not shown), approached the camera, a double image of the grid developed, as shown in Fig. 4. The displacement of these images was then interpreted to give the displacement of the grid as a function of time (obtained from the framing speed: 20,000 frames/s in Fig. 4). These results, for different distances between the explosive and the top of the steel plate, are shown in Fig. 5. The clearly shown stepwise displacement of the steel plate, rather than a smooth continuous one, has important implications in the development of theoretical interpretations of this complex process. This technique for meas-

uring plate displacements will certainly be applied in other areas where refined data of such plate motion are urgently needed.

R. Wyatt (3) discussed the design of an electric-spark detonator specially designed to be inexpensive and reliable, while having a spread in operating time of only about $\pm 1 \mu$ s. Such detonators are necessary for explosive experiments monitored by limited-access cameras operating in the megafame-per-second range. His detonator, shown in Fig. 6, has several features of interest to detonator designers, such as the use of a "conductive mix" of powdered aluminum and PETN, the variation of explosive-charge diameter as a function of charge length, and the velocity of the reaction front as a function of charge length (inferred

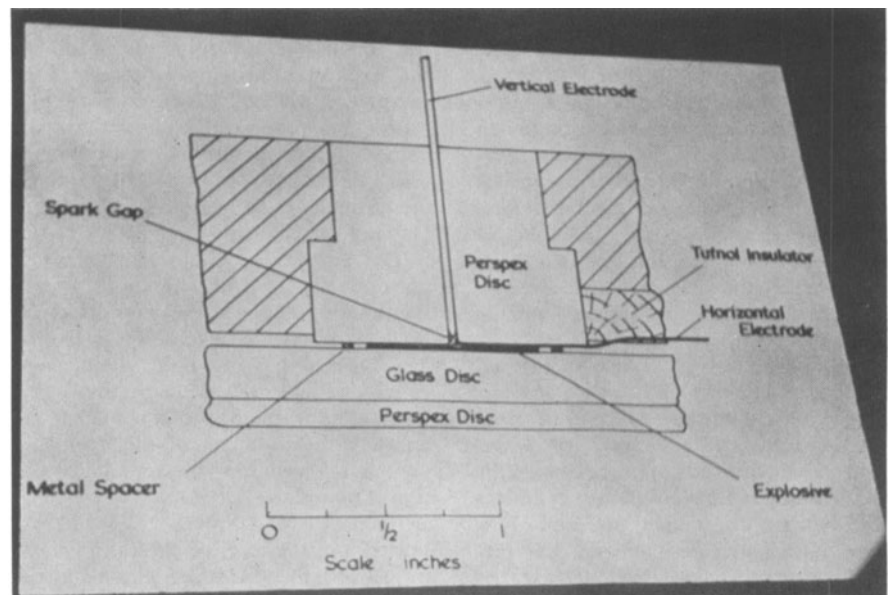


Fig. 1. Experimental arrangement: electric-spark initiation of nitroglycerin.

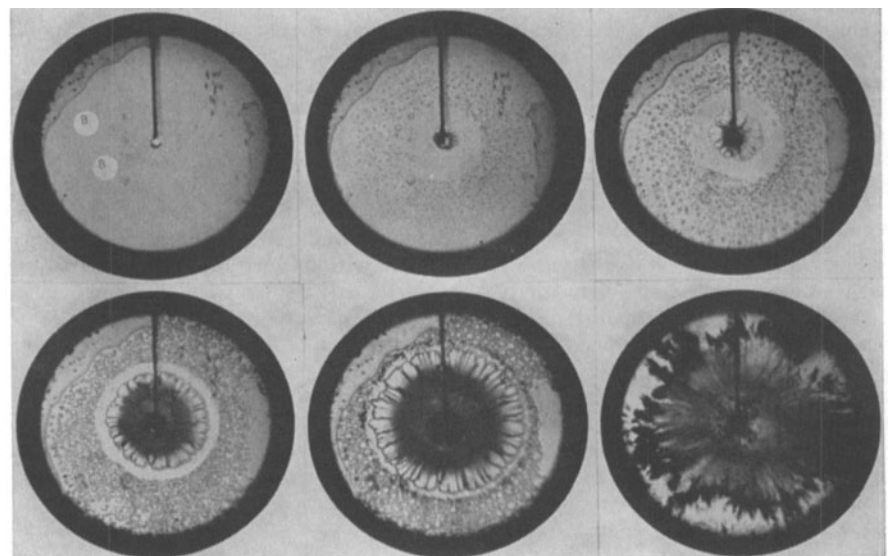


Fig. 2. Typical results in nitroglycerin-initiation studies.

A paper to be presented during the Society's 99th Conference in Washington, D.C., May 1–6, 1966, by B. E. Drimmer, Head of the Propulsion and Energy Conversion Branch, Research Div., Bureau of Naval Weapons, Navy Dept., Washington, D.C. 20360. (This paper was received March 24, 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, Hoffmanstr. 59, Germany.

† For U.S.A., typical examples include work done at Los Alamos Scientific Laboratory (Campbell, Ramsay et al.), U.S. Bureau of Mines (Van Dolah et al.), and Naval Ordnance Laboratory (Jacobs, Liddiard, Boyars et al.). In U.K. typical examples include work done by Bowden et al.

‡ K. R. Coleman; *Proc. 4th International Congress on High-Speed Photography* (1959), 32.

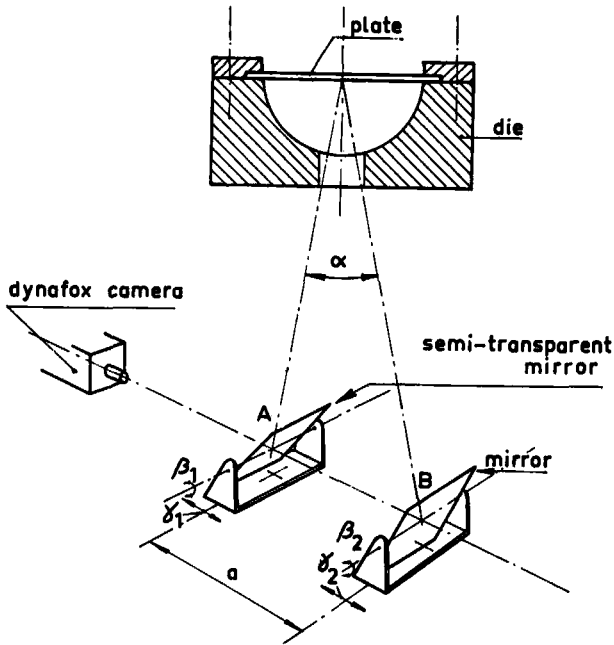


Fig. 3. Experimental arrangement: explosive forming.

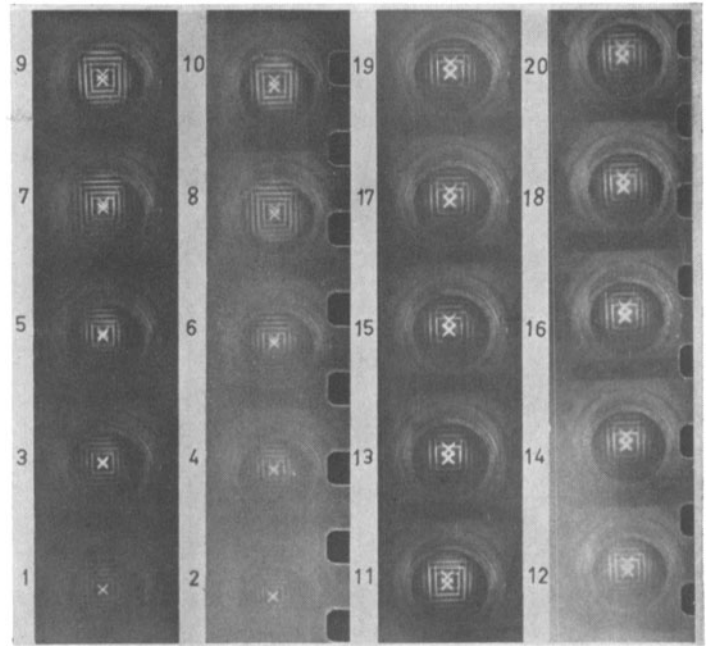


Fig. 4. Grid displacement in explosive forming.

from the data shown in Fig. 7). (The latter data were obtained from Beckman & Whitley Model 189 framing camera photos taken of the initiation of these detonators, though made with transparent plastic cases.)

The interrelated subjects of shock-wave collisions and implosions came in for examination by three speakers. R. S. Dennen (52) discussed cylindrically imploding shock waves generated by means of an electrically exploded film of silver deposited on the inner surface of a glass cylinder. His experimental arrangement, involving schlieren technique as shown in Fig. 8, permitted him to follow the progress of the cylindrically imploding shock wave to the axis, "and beyond" (i.e., its reflection outward). Comparison with theoretical calculations§ showed that the shock wave moved slower than predicted, and that no appreciable acceleration of the wave was observed in the vicinity of the centerline. However,

§ G. Guderley; *Luftfahrt-Forschung*, 19 (1942), 9, 302.

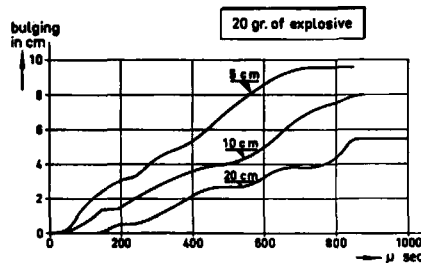


Fig. 5. Explosive forming: time dependence of displacement of steel plate for different charge-to-plate distances.

these conclusions are at variance with those of J. H. Lee and B. H. K. Lee^{||} who found close agreement with predicted accelerations of cylindrically imploding detonation waves. (It is possible that time-space resolution of the Beckman & Whitley Model 189 camera was not good enough to demonstrate this ac-

^{||} J. H. Lee and B. H. K. Lee; "Cylindrical Imploding Shock Waves"; *Phys. Fluids*, 8 (1965), 2148.

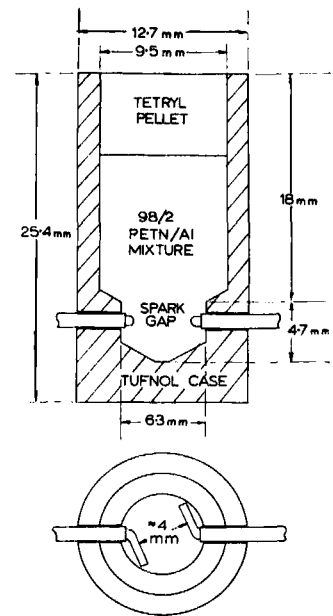


Fig. 6. Electric-spark detonator.

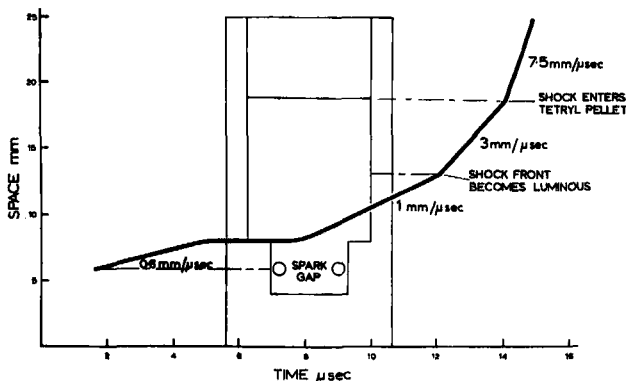


Fig. 7. Space-time curve for initiation of detonator of Fig. 6.

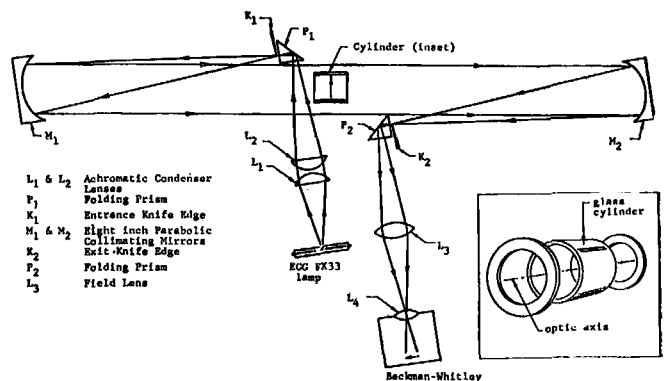


Fig. 8. Experimental arrangement for the study of imploding shock waves.

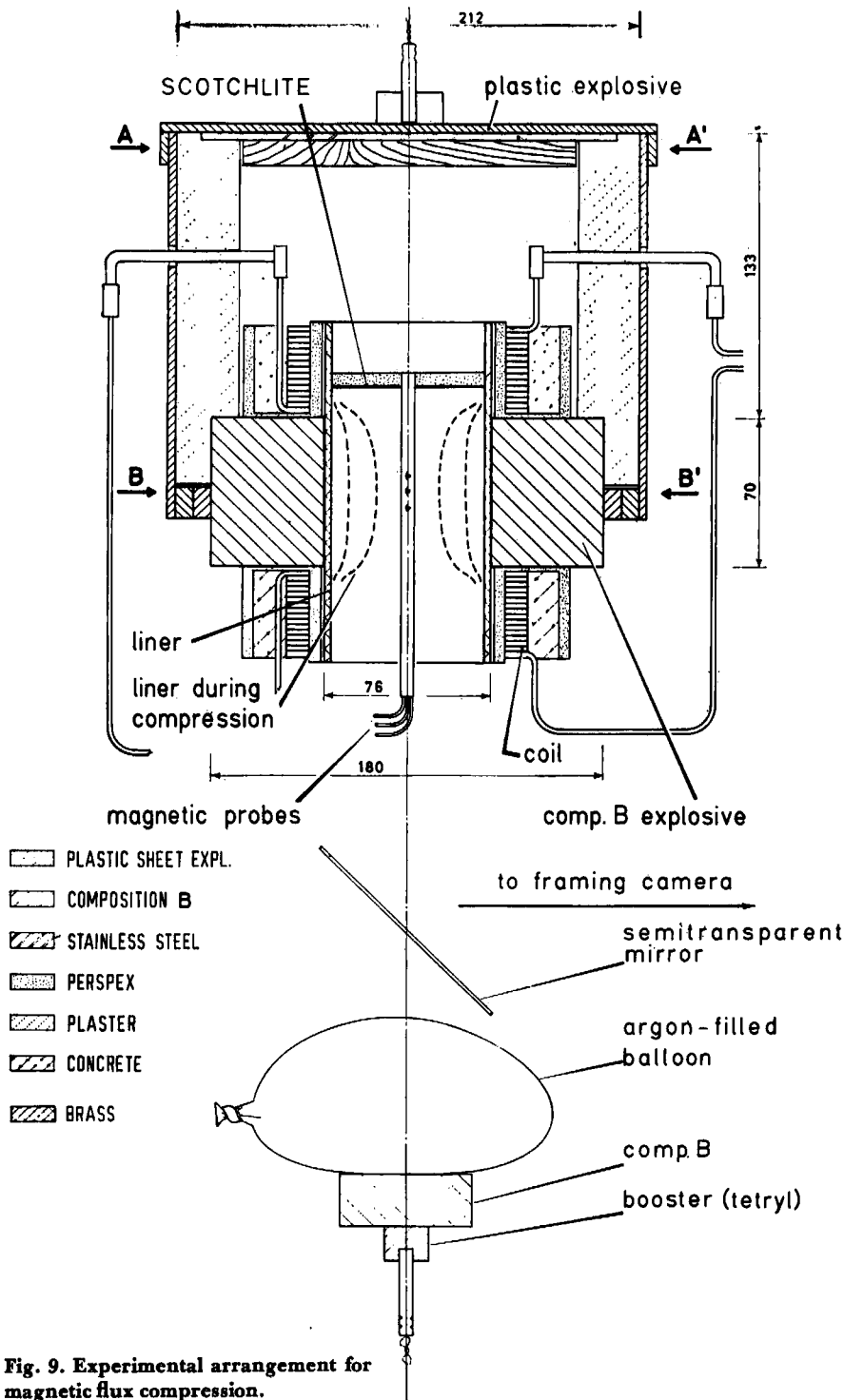


Fig. 9. Experimental arrangement for magnetic flux compression.

celeration, especially in the last 10% of the shock-wave trajectory. Lee used a streak camera to follow the implosion wave).

J. van Montfoort et al. (20) discussed an application of implosions: the explosive compression of trapped magnetic fields to create field levels measured in megagauss. In this report, he amplified the photographic aspects of their previously published paper[#] on magnetic flux compression. Their experimental ar-

angement, shown in Fig. 9, contains a number of features of much interest to experimentalists in magnetic-flux compression, as well as other aspects of explosive phenomena. Van Montfoort and his colleagues were able to build a new trigger circuit for their Barr and Stroud CP 5903/5905 camera, which permits automatic firing of the explosive charges at pre-selected intervals, with a precision of 0.1%. [This circuit is described in great detail in an internal report by the same authors (Internal Report 65/16; June 1965).] To take advantage of such precision, properly

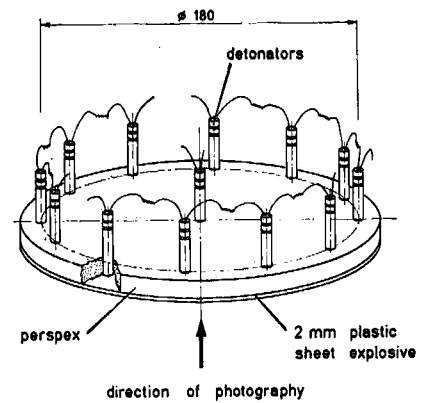


Fig. 10. Experimental arrangement for testing simultaneity of electrical detonators.

designed detonators were required, especially for those experiments involving the simultaneous initiation of several detonators. (Some of their experiments required as many as 24 simultaneously initiated detonators.) Their commercially obtained high-quality detonators were tested in an arrangement shown in Fig. 10. The resulting photographs, Fig. 11, clearly show the simultaneity of the 12 detonators (the central detonator was initiated 8 μ s after the main group).

The brilliantly-lit shock zones in Fig. 11, produced by the interaction of the shock waves, were the subject of investigations by D. D. Abernathy (46). He produced color photographs almost identical with those in Fig. 11, using a Beckman & Whitley Model 189 Framing Camera. Abernathy probed more deeply into the phenomena of such multiple detonation wave interactions by repeating these experiments and recording the detonation and shock-wave developments by means of a FEMCO flash x-ray unit capable of producing a 600-kV, 0.2- μ s output. Correlation between the two sets of photographs then permitted a quantitative analysis of the wave interactions, which will be of much interest to workers in the field of hydrodynamics of detonations and shock waves.

Precise data concerning the pressures, fire-ball contours and related items that develop because of accidental explosions and detonations in explosive factories, storage magazines, and the like, are most difficult to come by because, obviously, no one is prepared with appropriate cameras, etc. when the accidents occur. Y. Mizushima and M. Kusakabe (21) reported on Japanese Government experiments to develop "hard" data of this type, for ultimate use in promulgating appropriate safety regulations. The report, read at the meeting by their colleague, Professor S. Suzuki, was in the form of a series of film strips of Fastax camera shots showing the effects of detonations of up to 3 tons of dynamite. Of the 35 shots fired through 1964, six typical cases were selected for the film.

[#] F. Herlach, H. Knoepfel; *Rev. Sci. Instr.*, 36 (1965), 1088.

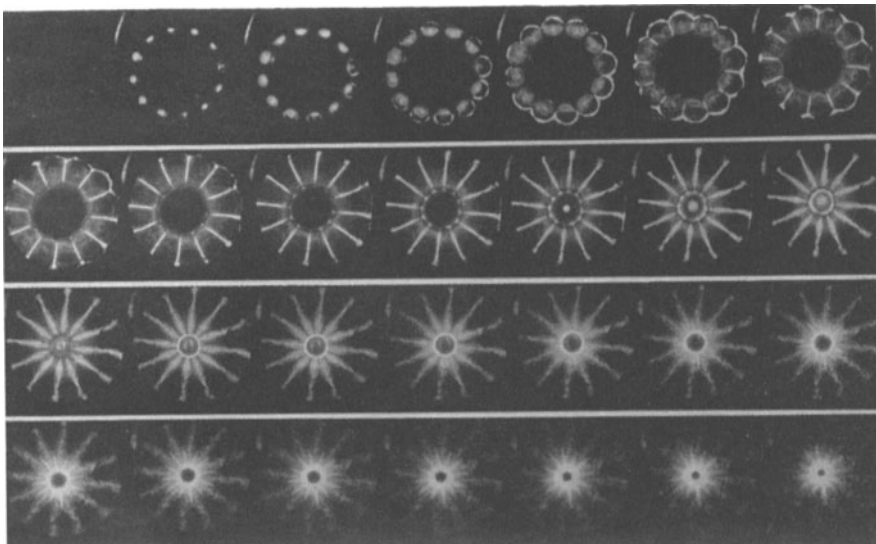


Fig. 11. Framing camera pictures of simultaneous initiation of detonators of Fig. 10 (central detonation delayed $8 \mu s$).

By careful analysis of these films, reasonably accurate pressure-time curves were obtained for the shock wave, and flame-front contours versus time for the fire ball. These accurate figures will be most useful, especially for precise definition of the zones immediately adjacent to explosive magazines, and explosive-loading workshops. The explosives used were mostly "commercial" (as distinguished from military, such as Composition B); e.g., "Shinkiri dynamite" (nitroglycerin : ammonium nitrate : nitrocellulose : naphthalene : wood meal or starch; approximately 30 : 64 : 1 : 2 : 3); "Karlit" (ammonium perchlorate : ferrosilicone : wood meal : oil; approximately 75 : 16 : 5 : 3); "Shinskoan explosive" (ammonium nitrate : sodium nitrate : ammonium chloride : TNT : dinitrotoluol : wood meal; approximately 64 : 15 : 10 : 7 : 2 : 3).

The study of electrically exploding metal wires was discussed in two papers. R. H. Christie (29) applied the light from a ruby laser to observe an exploding tungsten wire. The property of the laser used was the extremely high brightness; the coherence was not used, as in fact the light was diffused through a ground glass screen, opal glass, or thin white card in order to produce pictures free from large-scale graininess. Using a Barr and Stroud CP5 framing camera, operating at 4×10^6 frames/s and a Q-switched laser having a pulse length of 30 ns, clear, sharp pictures were obtained. His split-frame experimental arrangement, shown in Fig. 12, permitted him to photograph simultaneously the self-luminous picture of the wire on half the frame, and the back-lit (with laser light) wire on the other half. A set of typical photographs is shown in Fig. 13 where the laser light lasted long enough to illuminate only two frames. In this case one can clearly see in the laser-lit parts, the development of prominences on

the wire surface, which are barely discernible in the self-luminous half-frames.

The other article on exploding wires was a contribution by W. G. Chace (44). In his experimental arrangement, Fig. 14, Chace compared the photographs of exploding wires, simultaneously taken against a brightly lit background, and with x-rays. (He obtained his back light by electrically exploding aluminum-coated plastic film, sold in the USA for Christmas tree decorations — an inexpensive and efficient light source.) (In Fig. 14, "S" is a thin polyethylene film which acts as a shock absorber for the x-ray film.) In a typical result obtained by Chace, Fig. 15 (in this case he used selfluminosity for half of his picture, rather than back-lighting), it can be readily seen that ordinary photography records the surrounding plasma sheath, while x-rays penetrate the sheath to record the wire material itself. The superiority of the radiograph for analytical studies of wire-diameter growth as, say a function of time, is readily apparent from this picture.

Chace's work in the area of wire- and film-explosions is well known, and his article contains much information of interest to students of this interesting phenomenon.

In the field of detonations, plasma physics, shock dynamics, and the like, it is often desirable to photograph self-

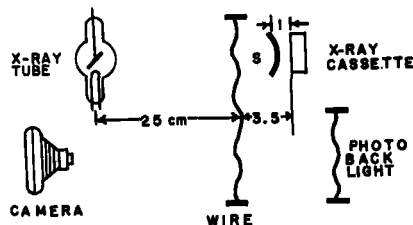


Fig. 14. Experimental arrangement for x-ray study of exploding wires.

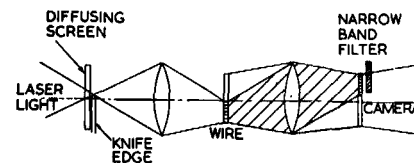


Fig. 12. Optical system for split frame photography of exploding wire. Portion of wire illuminated by laser light shown shaded.

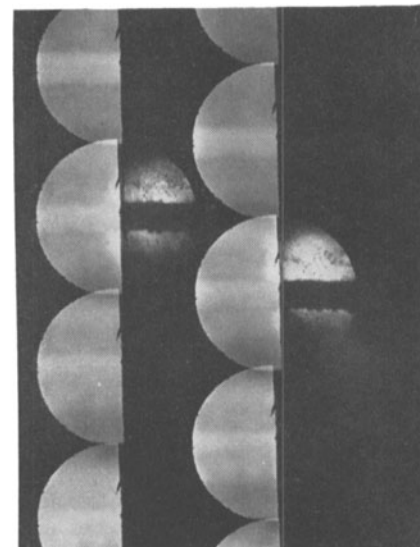


Fig. 13. Typical results of exploding wire back-lit by laser light (2 half frames), and by self-lumination (7 half frames). (Photo sequence is obtained by "zig-zagging" downward, from the right column to the left, back to the right, etc.)

luminous phenomena of very low light intensity. Various approaches have been used to overcome this problem, involving image intensification, and miniaturization techniques. J. K. Landre (14)

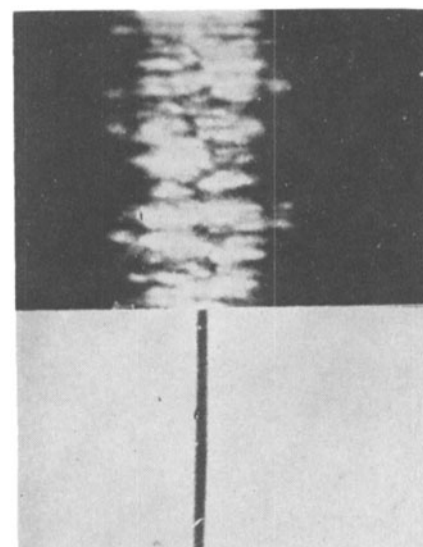


Fig. 15. Comparison of self-luminous photography and radiography as a method of observing a wire explosion.

described his latest streak camera which is addressed to this problem of low light intensity. The camera has a moderate writing speed (up to 5 mm/ μ s) and a high aperture ($f/2.8$ effective at the film plane). He detailed the design considerations which resulted in this

rotating mirror camera, which was specifically designed for use in the field of plasma discharges (such as in research of θ -pinch plasma discharges), but which might find application elsewhere where low-light intensity is a problem.

The author acknowledges, with gratitude, the aid of the authors of the referenced papers who kindly supplied preprint copies of their papers, and permission to publish a few typical illustrations.

Comments on Dynamic Photoelasticity and Fracture

By PAUL D. FLYNN

THIS BRIEF report deals with three papers on dynamic photoelasticity and two papers on fracture which were of interest to this reporter. Lord (93)* did not show any dynamic stress patterns, but he did present some interesting ideas on the possible use of bent beam compensators and image dissection techniques for determining low fringe orders in photoelastic models using white light and high-speed photography.

The problem of dealing with low

A paper to be presented during the Society's 99th Conference in Washington, D. C., May 1-6, 1966, by Dr. Paul D. Flynn, Pitman-Dunn Research Laboratories, Frankford Arsenal, Philadelphia, Pa. 19137. (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.

fringe orders in glass models was handled by Schwieger and Spuida (90) in a different way. They used the Sabbattier effect to obtain lines of equal intensity, or equidensity. These can be obtained by special processing from either a negative or positive image of a stress pattern. A beam in pure bending was used to calibrate the equidensity lines, and this was photographed along with the model under test. A two-dimensional circular ring under diametral impact was studied. Repeated tests and elastic impacts were produced by a steel ball suspended as a pendulum. Photographs were taken at different delay times using a xenon flash-tube without filters to obtain a sequence of dynamic stress patterns in a reflection-type polariscope.

Birefringent coatings were used by Pirodda and Berbenni (56) to determine transient strains in a simply supported beam impacted at the center. The model was made of annealed copper

and was stressed beyond the elastic limit. Single flash pictures were taken using a General Radio 1531A Strobotac and a Schott interference filter (4400 \AA) in a reflection polariscope. The moiré technique was used to obtain the contour lines in a simply supported circular plate loaded transversely. The authors concluded that the reproducibility of plastic deformations at low strain rates was adequate for single flash photography and repeated tests.

Fractures produced by exploding wires on the edges of glass plates were reported by Kerkhof (54). These were used not only to study the overall fracture pattern, but also to determine the type and intensity of the stress waves producing the fracture. The rates of crack propagation in materials of high elastic moduli were studied by Field and Heyes (61) and were compared with theoretical predictions. Bifurcation of a fracture due to stress wave interaction was shown.