HIGH-SPEED PHOTOGRAPHY

THERE has been an increasing interest in the techniques of high-speed photography and in their application. In October 1952 the Society of Motion Picture and Television Engineers of New York organized an International Congress on High-Speed Photography and held it in conjunction with its annual meeting in Washington. The number of people who attended and the extent of the interest were such that it was decided to hold other meetings, the next in Europe. The Second International Congress on High-Speed Photography was held under the auspices of the Association Française des Ingénieurs et Techniciens du Cinéma in Paris in September 1954. A great deal of material was submitted to this Congress and has been published recently*. These proceedings are an impressive indication of the breadth of the subject and of the extent of its applications. Sixty-eight papers were presented, and the proceedings are extensively illustrated, by some 650 illustrations, many of which include a number of separate pictures, so that the whole number of illustrations runs into the thousands.

As many major advances have been made in Britain, it was decided to hold the next Congress here. The Department of Scientific and Industrial Research agreed to sponsor the Congress, which was held in London during September. It is a measure of the extent to which the Congress was truly international that of the 330 members who attended, ninety-six were from overseas, representing fourteen different countries.

The papers for presentation were submitted to the editorial committee some months before the Congress. There was severe restriction of the length of the papers and of the numbers that could be accepted. Papers describing work which had been published elsewhere were automatically rejected. This strict editorial policy meant that papers presented and to be published in the proceedings are of a high standard, and describe new and original techniques and applications that are nowhere else available in the published technical literature. The papers were all preprinted and copies made available to members before the opening of the Congress. They were therefore not read *in extenso*, but each author gave a résumé of his work and indicated what advances there had been in recent months. Ample time was thus left for discussion and comment on each of the papers. One of the most valuable features of the whole Congress was the vigour of the discussion and the attention that could be given to individual problems, inquiries and suggestions. Summaries of the discussions will be included with the proceedings.

The main topics discussed at the different sessions of the Congress are indicated briefly below.

Flash light sources. There were considerable advances in the detailed study of sources and in the efficiency of conversion of energy for single-shot work (E. P. Tawil; D. P. C. Thackeray; M. Laporte; J. S. T. Looms and R. J. North; P. Devaux; I. S. Marshak); and in the development of equipment that could produce a series of short flashes at high rates (H. E. Edgerton; F. Früngel). Valuable work was also reported on the production of rect-

angular pulses of light suitable for illuminating an event while a whole sequence of pictures was taken (D. P. C. Thackeray). Analyses were also presented of the light source requirements, and how these could be met, for work in wind tunnels (L. H. Tanner; J. S. T. Looms and R. J. North).

Image-splitting and image-dissection techniques. New techniques were described which allow fast photography through a microscope with very simple equipment (J. S. Courtney-Pratt and D. P. C. Thackeray; J. S. Courtney-Pratt). A combination of image-converter and image-dissection techniques was described which allows a high throughput of light and which has already been used to take a sequence of fifty pictures at a rate of $5 \times 10^7/\text{sec}$. (G. H. Lunn). This technique is likely to be of far-reaching importance as already it gives very high rates and yet is nowhere near the limit to which it can be pressed. Further development work will be required but should be amply repaid, as fundamental limitations are unlikely to be restrictive for speeds higher still by a factor of 100 or 1,000.

Inertialess shutters. The use was described of image converters for taking single-shot pictures with an exposure of 3×10^{-9} sec. (R. F. Saxe), and an assessment presented of the efficiency of present-day converters and the extent to which their efficiency may be increased (R. A. Chippendale). It would seem that one may hope eventually to get an intensification of the image by a factor of 100 or so. Advances in the use of Kerr cells were described, and a valuable new method of switching the light beam from one path to another so that a short series of pictures can be taken at speeds up to the maximum operating speed of these switching cells (E. W. Walker). A combination of image dissection and Kerr cell aperture-scanning was described (J. L. Viard). As in this equipment the Kerr cells are of very small dimensions, the equipment can give a qualitative study of an event at even higher rates.

Applications in industry and biology. Two papers were presented on machine and combustion analysis (R. O. Painter; J. G. G. Hempson), and a paper was presented describing a study of the flow of blood corpuscles *in vivo* (A. M. P. Brookes and P. A. G. Monro). This paper described new techniques of much wider application than simply to the particular project for which they had been developed. A cathode-ray tube was used as a repetitive source, and it was shown that one could estimate the velocity of mean flow of a stream in which randomly distributed particles are transported, by a method similar to the stroboscopic study of consistently repetitive events. The authors likened the pattern that could be seen to raindrops on a windscreen. The pattern would show no drift if the frequency of flash was equal to the mean rate of passage of particles.

Application to ballistics and explosives. A large proportion of the development and use of high-speed photography has always been in the military field. A number of papers were presented in this and other sessions that described cameras developed for use in guided-weapon trials (R. Herden; P. B. N. Nuttall-Smith), in supersonic flight (J. S. Rinehart), in proof-range work (R. Herden; M. B. Prudence; J. H.

* "Actes de 2e Congrès International de Photographie et Cinématographie Ultra-rapides" (Dunod, Paris, 1956).

Waddell; M. Sultanoff; T. Uyemura and T. Morishige; P. Devaux; J. S. Rinehart; J. L. Viard; E. W. Walker; H. F. Hills; T. Uyemura; L. Zernow and G. E. Hauver), and in studies of safety hazards of the ignition of explosives and of gas mixtures (A. Berthmann and H. Käufer; M. Giltaire).

Instrument aids. Two papers were presented on more precise time measurement (P. Fayolle; W. Baur and K. Pfister), and a camera was described with a system that allowed the separation of pictures taken with different colour pass-bands (R. L. Aspden). A number of authors pointed out that similar means could be used to increase the framing rate, to increase the number of pictures in a sequence, or to differentiate between different features of an event (J. S. Courtney-Pratt and D. P. C. Thackeray; N. Dombrowski; W. D. Chesterman). A paper was presented in this session which described a method for studying the fracture process within a solid (F. Kerkhof). In the simplest case of brittle failure in tension, a straight fracture front will generate a plane fracture surface in a solid. If ultrasonic waves are present, the instantaneous direction of movement of the fracture front can be a little affected. After fracture, the ripples in the surface show how far the fracture front had advanced between successive maxima of the ultrasonic wave. This is a powerful method, as it allows one to study the shape and movement of a fracture front inside even an opaque material, whereas the ordinary photographic methods are restricted to a study of the movement of the crack at the surface.

Photographic materials. A number of papers were presented on the behaviour of ordinary and colour emulsions, with reference particularly to their behaviour at short exposure (R. J. North and N. A. North; J. Eggert and R. von Wartburg; R. von Wartburg; J. Castle, W. Woodbury and W. A. Shelton). Many emulsions show reciprocity failure by a factor of 2 or 3 for exposures between 10^{-2} and 10^{-5} sec. It used to be thought that there might be even greater reciprocity failure at shorter times still; but most of the evidence produced at this Congress indicates that the sensitivity of the emulsions is not much further reduced for exposure times as short even as 10^{-9} sec. (H. Hoerlin).

X-rays. Papers were presented on ciné-radiography of biological subjects at rates up to 125 frames per sec. (S. A. Weinberg, J. S. Watson and G. H. Ramsey), and on a study of the movement of shock waves in solids by the use of flash X-ray bursts of duration between 10^{-6} and 10^{-7} sec. (R. Schall). There was also a valuable paper describing a critical study of the role and influence of gas in X-ray tubes (R. F. Thumwood). It was shown that the efficiency could be greatly increased by controlling the pressure of gas with an optimum at pressures in the range 10^{-3} to 10^{-4} mm. mercury.

Film evaluation. Papers were presented describing methods of reading films, and of data processing (B. S. Benson; W. N. McJilton; J. Rieck). This is a problem of growing importance, as with the increase in speed the number of frames to be measured has made this the most laborious operation of the whole investigation; so much so that considerable increase in the complexity of recording equipment is amply justified if it can lead to a more direct means of assessment.

Optical techniques. Contributions were made describing installations that made use of the Cranz-

Schardin system, of interferometric and schlieren techniques (H. F. Hills; H. Schardin; J. Dyson), and of an optical system that combined some of the advantages of phase-contrast and schlieren systems (R. Bouyer and C. Chartier). There was also an elegant new method described for extending the range of schlieren systems utilizing the moiré patterns that can be obtained by the use of two separated grids (T. Fromme).

Rotating mirror cameras. Several new cameras were described (B. Brixner; A. E. Huston; T. Uyemura; L. Zernow and G. E. Hauver; J. Tchernyi), and there was a vigorous discussion of the limitations of such systems from considerations on one hand of diffraction limits and the ultimate strength of materials, and on the other by the technical difficulties of manufacture of components of sufficient quality. Prof. H. Schardin showed that for rotating-mirror framing cameras and streak cameras the product of the framing-rate and the number of lines resolved across the frame in the direction of movement of the image could not with present materials be made higher than 4×10^9 sec.⁻¹. One thus has a valuable criterion for assessing the performance of a camera by seeing how nearly this limit is approached. It became evident from the discussion that one might considerably surpass this limit if one took advantage of the principles of image dissection or the increased sweep-rate with image-converter cameras, and might well go even further by combinations of dissection and image converters.

Medium repetition-rate cameras. Cameras were described that showed considerable advances in resolution, and consistency of operation even under adverse conditions (B. W. Allwood, J. R. Bouffier, B. B. E. Death and D. Jones; J. H. Waddell; R. Herden; P. B. N. Nuttall-Smith); and also a system that allowed rapid acceleration of a loop of film to avoid the long delay and film wastage that often occurs in more conventional equipment (M. B. Prudence).

Applications to fluid dynamics. Papers were presented describing installations for studying flow in wind tunnels and in water (H. P. Liepman and J. B. Cooper; F. Früngel, E. Baillitis and W. Thorwart), in shock tubes (H. Schardin), and water entry tanks (E. G. Richardson). Methods were described for studying droplet formation (J. G. A. de Graaf; R. P. Fraser and N. Dombrowski) and jet disintegration (Y. Kumano). An interesting series of pictures was presented which showed the extraordinary differences in the detail that were visible with different methods of illumination (R. P. Fraser and N. Dombrowski). This was a salutary reminder that one must not assume that things are not there if they cannot be seen on a photograph. Attention to the details of the technique can perhaps make them evident.

Review papers. Colonel P. Naslin opened the technical sessions of the Congress by presenting a paper on the state of the art. As his main topic he drew an analogy between the practices and principles of high-speed photography on one hand, and the developments in control and information theory on the other. One may record continuously the variation of amplitude of one or another of the parameters, or one may sample the value of a number of parameters at a given instant (as in ordinary intermittent-movement ciné cameras). One may, however, sample in other dimensions, and dissection systems are typical of this. One might also sample, quantize,

code, or multiplex other variables, so that one could raise to the maximum the rate of recording of those features of the incoming information that are most relevant. A consideration, then, of the similar advances in communication theory can stimulate advances in the whole field of high-speed photography.

A review of the work of the Congress was presented on the last day (J. S. Courtney-Pratt). Advances in particular techniques were commented upon. Trends of design were indicated. A summary was given of the emergence of principles of assessment with emphasis on the contributions, mentioned above, of Colonel Naslin and Prof. Schardin.

An exhibition was held in conjunction with the Congress, and a review has been prepared by A. R. Michaelis. This was by far the most comprehensive display of equipment for use in high-speed photography that has ever been held in Britain, and included exhibits from commercial firms, from government departments, and from universities, ranging from equipment that could be bought 'off the shelf' to research equipment that is in the process of development. It was significant that equipment that was described for the first time at the Congress in Paris is now in use at a number of laboratories and was on display at this Exhibition.

The published Proceedings of the Congress, including the review papers and summaries of the discussion and a brief description of the Exhibition, will be available from Butterworths Scientific Publications, London, in January 1957.

At the Congress the range of topics covered indicates the growth and breadth of the subject. Photographic methods are among the most powerful of the tools we have. The study even of processes we think of as slow requires short exposures and high repetition-rates when the interest is in the fine detail; and more and more we must rely on the techniques of high-speed photography. For studies on the microscopic scale the problem is accentuated, and we must take advantage of the most advanced and elaborate of the new techniques, and also must apply research and development effort to the improvement of these techniques. The ever wider use of high-speed photography in research and industry is a foregone conclusion, and it is as certain, too, that this will contribute to more rapid progress in science and technology.

J. S. COURTNEY-PRATT

THEORETICAL CONSIDERATIONS ON GRINDING

A SYMPOSIUM consisting of five papers on various aspects of grinding was held by the Institution of Chemical Engineers at the Royal Institution on November 7, under the chairmanship of Mr. A. S. White.

The first paper, by Dr. H. E. Rose (King's College, London), dealt with an attempt to predict the principal features of ball-mill behaviour from purely theoretical considerations. The basis of the method is to use suitable probability functions to compute the probability of a particle entering a 'zone of operation' around a contact point between a pair of balls and to compute the probability of occurrence of some process after the particle has entered this 'zone'.

From this reasoning it is possible to predict a number of features of ball-mill performance which, although they have been observed in practice, have not, so far as is known, been predicted theoretically. From such considerations it was suggested that, in certain circumstances, the ball-wear may be reduced by the use of softer metal; that the rate of grinding may be increased by the use of a reduced powder charge in the mill, although this can only be accomplished at the expense of increased rate of metal wear; and that the relationship between the surface produced and the time of milling is a function of the relative hardness of the balls and the material being ground.

A second paper by Dr. Rose was an attempt to analyse the performance of a vibration mill, by the application of the method of dimensional analysis; the justification of this paper being that the vibration mill appears to offer the possibility of very rapid milling of certain classes of materials which are otherwise difficult to pulverize.

The treatment has led to the conclusion that the rate of grinding in a vibration mill varies as a fairly high power of the frequency and of the amplitude of the vibration; furthermore, the exact relationship between the rate of grinding and the frequency and amplitude depends upon whether the energy to produce new surface or the limiting stress in the particle is the criterion for comminution.

By analysis of the published data, it was shown that the rate of grinding is proportional to the density of the ball material, and that the maximum rate of grinding is achieved when the powder in the mill is just sufficient to fill the space between the balls.

A paper dealing with the application of the principle of similarity to mills and to the grinding process was presented by Prof. A. H. M. Andreasen (Royal Technical University, Copenhagen).

In this paper it was shown that geometrically similar jaw crushers, cone crushers and similar machines, in which the stressing of the particle is brought about by mechanical means, will operate at the same efficiency regardless of size, but the throughput will vary as the cube of the size. For edge-runner mills, however, in which the stressing of the particle arises from gravitational forces, the throughput and energy consumption both vary as the square of the linear dimensions when the peripheral speed is constant; and as the cube of the size when the speed of rotation is fixed. With hammer mills, the condition for similarity is that the peripheral velocities must be constant irrespective of size and, under this condition, the production will vary as the square of the size of the mill.

For mills in which the inertial forces are produced by gravity, for example, the ball mill, the condition for similarity is that the densities of the grinding media shall vary inversely as the scale ratio of the machines. Since such materials are not available, true similarity cannot be maintained, and this is probably the reason why very small ball mills are not usually very successful.

When dealing with the principle of similarity applied to the crushing process, Prof. Andreasen showed that his experiments gave rise to orthogonally affine undersize curves for the product and, furthermore, it was shown that such curves would be predicted from an analysis of the fracture pattern obtained when solid bodies are crushed in a press.