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Optical Instruments for High Altitude Nuclear Tests

The JOWOG-13 Optical Instrument Subwog (U)

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

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Optical Instruments for High Altitude Nuclear Tests
The JOWOG-13 Optical Instrument Subwog (U)

by

H. Milton Peek

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OPTICAL INSTRUMENTS FOR HIGH ALTITUDE NUCLEAR TESTS

THE JOWOG-13 OPTICAL INSTRUMENT SUBWOG

H. Milton Peek

ABSTRACT

High speed cameras and spectrographs are useful diagnostic tools in nuclear weapons tests. High altitude weapons test applications require new, advanced, sophisticated designs not usually available from established commercial optical instrument firms. In 1964 an Optical Instrument Subwog of JOWOG-13 was established to promote the development of new instruments needed for weapons testing. Subwog work has resulted in development of the following:

1. the Model 739 rotating-mirror camera, being developed at Lawrence Radiation Laboratory. It will use an achromatic optical design developed by the United Kingdom Atomic Weapons Research Establishment and Los Alamos Scientific Laboratory;
2. the E 12 image-converter camera, a multiframe and streak camera capable of 10-nsec exposures, designed and developed at AWRE. A commercial unit, the Imacon, is available from John Hadland (P. I.), Ltd.;
3. the E 14 image-converter cameras, very high spatial resolution cameras under development at AWRE;
4. SPREFS, a space-resolving, fast framing spectrograph designed and built by AWRE;
5. the M 9 spectrograph, an f/2, high resolution spectrograph, designed and built by the Regulus Co., now a subsidiary of EG&G, Inc.
6. a scanning Fabry-Perot interferometer of 2-in. aperture, suitable for use in jet aircraft, developed by AWRE; and
7. an x-ray grating spectrograph which successfully diffracts x rays of 0.3- to 50-Å wavelength, developed by AWRE and the UK National Physical Laboratory.

Other problems under study by the Subwog include (1) an all-sky camera capable of framing rates up to 1000 fps, (2) a near-infrared spectrograph using infrared image intensifiers, and (3) an f/1 scanning monochromator with 5-Å/mm dispersion. Most of this work, including field testing and evaluation by participating JOWOG laboratories, will probably be complete in about two years.

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INTRODUCTION

During planning for the Los Alamos Scientific Laboratory (LASL) optical experiments for Operation Dominic (1962) it became clear that some important phases of high altitude weapon physics could not be investigated because of a lack of optical instruments with adequate time, spectral, and spatial resolution. These shortcomings became more evident during and after the operation when analysis of the results was started. In particular, the lack of two general types of information, namely (1) very early time photographs with sufficient time resolution to show the size of the fireball and the initial debris distribution, and (2) spectroscopic data for wavelengths less than 3000 Å, made correlation of experimental and theoretical data difficult. Probably the best examples of these problems are the analysis of the Bluegill event by Zinn[1] and the continuing analysis of the Checkmate event by Bethe[2] and Sappenfield.[3]

During 1963, at about the time of the Multilateral Nuclear Test Ban Treaty, LASL turned to development of the more sophisticated optical instruments that would be needed in future tests. The most important were (1) a camera achromatic over the 3000- to 9000-Å wavelength range and capable of fractional microsecond time resolution with spatial resolution limited only by atmospheric seeing conditions, (2) a spectrograph capable of 10-μsec (or less) time resolution with about 5-Å spectral resolution, but also capable of two-dimensional space resolution, and (3) a continuous-writing, rotating-mirror camera achromatic over the 3000- to 9000-Å wavelength range and capable of a 10-μsec (or less) time resolution. A further requirement was that these instruments be safely operable in jet aircraft.

Requests for proposals to build these instruments were sent to many suppliers of optical instruments, including the British firms of Barr and Stroud, Ltd. and John Hadland (P. I.), Ltd. who, in turn, referred the requests to the United Kingdom Atomic Energy Authority's Atomic Weapons Research Establishment (AWRE), the principal British source of optical instrument designs of these types. These requests led AWRE to propose to LASL the formation of a working group under the sponsorship of JOWOG-13. The group's mission would be to formulate specifications for optical instruments needed for nuclear test applications, to determine whether such instruments could be obtained from commercial sources, and, if not, to recommend how such instruments could be developed within the participating laboratories. This group, the Optical Instrument Subwog of JOWOG-13, had its first meeting at AWRE, Aldermaston, on April 21 to 22, 1964. They have met six times since, most recently at AWRE on October 8 to 10, 1968. (See Appendix A for a list of Subwog membership and meetings.)

This report describes Subwog efforts to promote the development of optical instruments for use in nuclear testing and discusses applications of specific instruments, specifications and performance of instruments that have been developed, the status of instruments still being developed, and possible future work.

OPTICAL PHYSICS OF NUCLEAR EXPLOSIONS

Optical instruments and techniques have been used for many years to obtain diagnostic information from sea level nuclear tests; e.g., hydrodynamic yield is obtained from the dimensional time history of the fireball as recorded by cameras. Other diagnostic data have been determined from time resolving, interference filtered photometers which record the air fluorescence induced by the gamma-ray output of the bomb. The extent to which optical techniques have been used in diagnostics and weapon effects experiments in high altitude tests is not well known, perhaps because of the relatively few high altitude tests conducted.

Knowledge of the various phenomena which can occur in high altitude nuclear explosions is essential in planning the development of new instruments. One classification of these phenomena can be made by following the time history of the energy release from the bomb and its coupling to the atmosphere. Gamma, x-ray, and neutron emissions are essentially complete in the first microsecond after detonation. For a "nominal" bomb of the type described by Glasstone,[4] the prompt gamma- and neutron-radiation path lengths correspond to the atmospheric column density above about 30 km, i.e., 2 to 3 x 10^{-2} cm^2/g. Consequently, if the burst altitude is above 30 km, there is a significant volume of the atmosphere in

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which fluorescence is induced by absorption of gammas and neutrons, but this fluorescence is short-lived. At lower burst altitudes, fluorescence is confined to a much smaller volume, e.g., at sea level a sphere of about 300 meters radius. For a nominal bomb only a few percent of the total yield is radiated as gammas and neutrons. However, some three quarters of the total yield is radiated as x rays whose path lengths correspond to atmospheric column density above about 100 km. Consequently, if the burst occurs much above 100 km, a large volume of air at altitudes near 100 km is strongly excited and significant air fluorescence occurs. However, if the burst occurs much lower than 100 km, the x rays are absorbed close to the burst point in a nearly spherical region which is highly ionized and heated. This region of excited air is called the x-ray fireball. The energy in the x-ray fireball interacts with the still undisturbed air farther from the burst point and results in radiative expansion of the fireball and hydrodynamic motion of the heated air in the fireball. All these phenomena are observable by well-known techniques of high speed photography and spectroscopy.

Following the prompt radiations there remains the bomb debris which carries about a quarter of the total bomb yield as kinetic energy. Several debris-related phenomena can be studied by optical techniques. One is the very early motion of the debris, e.g., the disassembly of the weapon case during which direction and velocity are important. Whether such observations are successful depends not only on the characteristics of the optical instruments, but also on the burst altitude. In particular, the burst altitude must be high enough that essentially no x-ray fireball is formed, or at least that the x-ray fireball be optically thin for those wavelengths used to observe the debris motion. Another important phenomenon is the emission of ionizing ultraviolet radiation by both the debris and the mixture of debris with swept-up air that is created in the early motion. This is important in understanding the energy partitioning of the total yield, but perhaps more important because the ionizing radiation may get far enough from the burst to cause widespread, long-lived blackout for HF and radar frequencies. The "ultraviolet fireball" of the Checkmate test of Dominic is probably the best example of this phenomenon.

Two other closely related phenomena are the debris motion as it mixes with or "snowplows" into the air and the subsequent formation and motion of the shock generated by the debris-air mixture. Again, depending on the burst altitude, the early motion and mixing of the debris with the air may not be observed unless the x-ray fireball is absent or transparent to (usually) visible wavelengths. If the early motion is not observable, then the first sign of these phenomena is the appearance of the debris-generated shock just after it has caught up with the shock generated by the heating from the x-ray deposition. However, as burst altitude increases and air density decreases, the debris/debris-air shock phenomenon may not occur. Instead, only a piston or debris-air snowplow is evident. At still higher altitudes, the snowplow is hard to detect by optical means, and other techniques are required to study the debris motion.

Detailed observations of these phenomena are important in understanding the interaction of the bomb debris with the geomagnetic field. At sufficiently high altitudes this geomagnetic interaction leads to still another phenomenon, namely, the formation of ionized regions, sometimes called "pancakes," at the northern and southern magnetic conjugate points along the geomagnetic field line through the burst. That is, the fission betas and debris ions travel along geomagnetic field lines to the north and south and are captured in the atmosphere at different altitudes depending on their energy. The radiation resulting from beta or debris ion capture in the atmosphere is similar in wavelength distribution to the air fluorescence induced by x-ray absorption. However, the "pancake" radiation lasts for a while because of the spread in velocity of the debris and concomitant betas: e.g., for the Starfish test the northern conjugate pancake[5] was recorded by cameras for several minutes after burst. These geomagnetic interaction phenomena are important in missile defense system problems because of their effects on radar transmission.

The remaining important magnetic phenomenon is the late time motion of the debris for altitudes at which the debris kinetic energy is deposited in regions close to burst point, i.e., within a few tens of kilometers. For these altitudes there is a significant debris or debris-hot air cloud which cools as it rises. This cloud may have sufficient ion and electron density to black out HF and radar transmission, and, depending upon burst altitude, may remain significantly ionized for many minutes as it rises and spreads slowly along geomagnetic field lines.

While there are other optically observable phenomena which may be more or less important than those mentioned here, this discussion should serve as a background for the instrument design problems considered by the Subwog. It will be obvious, subsequently, that many of the instruments studied are useful not only in high altitude nuclear testing studies but also in low altitude, or even underground, nuclear tests and in other experiments where bright, rapidly changing sources are studied.

OPTICAL INSTRUMENTS

The instrument needed for nuclear test applications to provide spectral- and time-resolved photographs of the bomb could be called a "spectrokinebombograph." However, because of the wide wavelength range and the required wavelength resolution, and because of the large time spread and the required time resolution, it is not possible to build a single instrument that meets all requirements. Therefore, the problem must be solved by devising some set of instruments having different spectral, time, and spatial resolution capabilities. This set will be composed of cameras, spectrographs, and photometers or radiometers. By a camera we mean a device that makes and records an image of a source, generally in some broad range of wavelengths, on photographic film or on some other detector that affords two-dimensional space resolution. By a spectrograph we mean a device that makes (usually) a narrow band record of the radiance distribution at the entrance aperture of the device; i.e., an ordinary slit spectrograph is an instrument that makes wavelength-resolved pictures of the entrance slit on photographic film. Spectrographs usually have space resolution only in the direction of the slit length, but if astigmatism and other aberrations are large, even this spatial resolution capability may be missing. By a photometer, better called a radiometer, we mean a device that measures the light flux falling on its entrance aperture. A radiometer has spectral resolution determined by the band pass of a filter in its optical path, but it does not have spatial resolution. Cameras and spectrographs usually achieve time resolution by two methods: sweeping the image across a stationary film, and moving the film past a stationary image. In general, the former technique is capable of much higher time resolution than the latter. In radiometers the time resolution capability comes from the time response capability or bandwidth of the photoelectric transducer and electronic signal conditioning equipment used to record the radiometer signal.

Because it is difficult to get, simultaneously, spatial, spectral, and time resolution, cameras are most often used to take time-resolved photographs from which the spatial distribution of source radiance may be obtained. The radiance data usually have little or no spectral resolution. Depending on the time resolution and the field of view of the camera, these photographs can provide information about early debris motion, radiative expansion, hydrodynamics, intermediate to late time debris motion, and magnetic effects. Slit or slitless spectrographs (giving either one-dimensional or no spatial resolution) are used to give data on the source spectrum. The extent to which the spectral data and the camera data are comparable and complementary depends on the time resolution capabilities of the spectrographs, their fields of view, and the temporal and spatial rates of change of the source spectrum. Radiometers are most useful when the spatial and spectral character of the source are essentially known and it is required to measure the time history of the light signal in the field of view of the instrument. Probably the best example of this kind of experiment is the time history of the x ray or gamma induced air fluorescence. Other examples are studies of late debris motion and magnetic interactions which result in widespread excitation of well known atmospheric emission lines as well as the line spectrum of the excited debris ions.

Table I describes a set of instruments which can be used to study high altitude nuclear weapons effects. Some are commercially available; some are prototypes, and the others are still being designed. Each tabulated instrument in which the Subwog has been involved is described in detail below. Other instruments, not usually called cameras or spectrographs, which are useful in high altitude weapons effects experiments are also described.

Cameras

Model 739 Camera. The Model 739 camera is intended to provide dimensional and radiometric data on the fast, early time radiative expansion of the x-ray fireball and the early debris motion. The most important specifications are frame rates up to about 3×10^5 fps with exposure durations as short as 1 μsec. Another important characteristic is that the camera optical system be achromatic over the wavelength range from 3000 to 9000 Å; thus, the camera will be sensitive to wavelengths ranging from the ozone atmospheric cutoff at about 3000 Å to the long wavelength limit of sensitivity for film emulsions normally used in field experiments. The mechanical design must be such that the camera is safe to operate in high altitude jet aircraft; i.e., if the rotating mirror should rupture, the housing will contain the resulting fragments so that they will not puncture the aircraft skin.

Design of such a camera was started in 1964. The initial work resulted in two proposals from the Beckman-Whitley Corp. The first was almost entirely a reflecting optical system, the only refracting component being a quartz wedge said to be an aberration corrector. This proposal was rejected by the Subwog because (1) it was doubtful that the design would meet specifications and (2) the Beckman-Whitley Corp. was not able to demonstrate the required compliance, even though it was said that a prototype or breadboard model of the optical system had been built and tested to specifications. The second proposal was essentially an all refracting system which contained so much glass that the effective wavelength range of sensitivity cut off at about 4000 Å. This proposal was also rejected.

Subsequent work at AWRE led to the conclusion that a nearly optimum design would be similar to the LASL Model 6 or Model 7 cameras designed by Brixner.[6] Further work by Bernard S. Brown at AWRE resulted in the construction of a single frame breadboard model (i.e., a straight through system without a rotating mirror) that seemed to give good resolution. Since then Lawrence Radiation Laboratory (LRL) has undertaken adaptation of the preliminary AWRE achromatic design to a complete prototype camera, using mechanical designs and construction and testing techniques developed at LRL in their work with Model 6 cameras. Preliminary, probably overly optimistic, plans call for construction of the prototype (but not full testing) to be complete by summer of 1969.

Slow All-Sky Camera. Experience during the high altitude events in the Dominic test series and in several more recent field experiments showed that the use of the so-called fisheye lenses on standard 35-mm cameras, e.g., the Flight Research "Multidata" camera, gave almost useless photographs because of small image size (only 6-mm diam), distortion, and lack of resolution. Other undesirable features were the small aperture (f/6) of the lenses available, and the lack of film transport mechanisms capable of a variety of interframe times.

At the request of LASL, work was started at EG&G about 1965 to get a reliable, f/1, 70-mm all-sky camera. After lengthy negotiation with possible manufacturers, it became clear that such a camera was essentially a "state-of-the-art" problem which would require considerable development. In October 1968, EG&G let a contract with the Pacific Optical Division of Chicago Aerial Industries, Inc. The resultant camera, the Pax-71, will provide a 54-mm diam image on 70-mm film, will have an aperture of f/1, and will have interframe rates up to 4 fps. The field of view of the lens is 165°. It is expected that the first camera will be delivered to EG&G for testing by summer of 1969.

Fast All-Sky Camera. In addition to the rather slow all-sky camera described above, it is highly desirable to have a considerably faster framing rate capability. The difficult optical design problem is a wide field of view lens with a long back focal distance. If this could be solved, a fast acting shutter mechanism such as a rotating prism, perhaps with a rotating disk, could be placed between the back lens element and the focal surface.

Following discussion of this problem at the sixth Subwog meeting in March 1968, Colin Reid of AWRE made a prototype lens with a field of view of about 150°, f/5 aperture, and about 50-mm back focal

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Table I. Optical Instruments for High Altitude Nuclear Weapons Effects Experiments

A. Photographic Cameras

Name	Maximum Frame Rate (fps)	Minimum Exposure Time (sec)	Maximum Aperture	Film Size (mm)	Frame Size (mm)	Remarks
Model 739 Camera	3×10^5	10^{-6}	f/20	35	15 diam	Rotating mirror type, achromatic over 3000- to 9000-Å wavelength range.
Dynafax Model 317	2×10^4	10^{-6}	f/11	35	18 x 24	Rotating mirror type made by Beckman-Whitley.
Photosonics 4B	3×10^3	10^{-5}	f/2	35	18 x 24	Rotating prism with disk shutter, 1000-ft film capacity, made by Photosonics Corp.
Photosonics 10B	360	10^{-5}	f/4	70	57 x 57	Rotating prism with disk shutter, 400-ft film capacity.
Fast All-Sky Camera	1000	10^{-4}	f/5	70	50 diam	Lens being developed in Subwog, minimum field of view 100°, requires "long" back focal distance to allow for shuttering and film motion.
Mitchell, High Speed	100	10^{-4}	f/2	35	18 x 24	Modified commercial model of existing movie camera made by Mitchell Camera Co.
Pulse Camera	10	2×10^{-2}	f/1	70	58 x 58	Camera does not exist; must be reliable, trouble free for field use; pulse timing from 10 frames per sec to much slower.
Slow All-Sky Camera	4	4×10^{-2}	f/1	70	54 diam	Field of view 165°; camera being built by EG&G and Pacific Optical Corp.

B. Image Converter Cameras

Name	Maximum Frame Rate (fps)	Minimum Exposure Time (sec)	Maximum Aperture	Film Size (mm)	Remarks
E 12	6×10^7	10^{-8}	f/1	35	Spatial resolution about 5 lp/mm; can also be used to streak to give time resolution of better than 10^{-10} sec.
E 14 G	(a)	10^{-7}	f/20	70	Spatial resolution limited by atmospheric seeing; intended for ground based use.
6 E 14	(a)	10^{-7}	f/20	70	Aircraft mounted instrument; field of view 3°; six frames.
E 16	single frame	ungated	f/1.2	sheet film	Image intensifier camera for use with STL/TRW Model 1 image converter camera; exposure gain of 60; 1-in. aperture.
E 17	(a)	(a)	f/1.4	sheet film	Continuous access circular streak camera.

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Table I. Optical Instruments for High Altitude Nuclear Weapons Effects Experiments (continued)

C. Spectrographs

Name	Aperture	Dispersion (Å/mm)	Wavelength Coverage (Å)	Resolution (Å)	Remarks
SPREFS	f/3.4	50	3000 - 9000	5	Space resolving, framing spectrograph; maximum speed 10^5 fps.
M9	f/2	2 to 9	2000 - 9000	0.01 - 0.1	Optically fast, high dispersion; one frame covers at least 1200-Å wavelength range in a 25-mm circular field on 35-mm film; can be used framing to give exposures of several μsec with interframe times of several msec.

(a) See detailed descriptions in text.

distance. The lens was shown at the seventh meeting in October 1968, but no test results were available then. No definite plans for development of the camera can be made until this prototype lens has been evaluated.

Image Converter Cameras

E 12. The AWRE E 12 image converter camera was not specifically intended for high altitude weapons test applications; it was being developed at AWRE[7,8] before the Subwog was started. The E 12 camera uses an image converter tube originally designed by Walters and Chippendale[9] and subsequently produced by several British tube companies. The tube is unique in that it has shutter plates as well as deflection plates. Both sets of plates are used in framing, while only the deflection plates are used to record streaks.

The E 12 camera system developed at AWRE[10,*] combines the fore-optical system (to image the source on the image converter photocathode), the image converter tube with driving and control electronic systems, and the camera optical system which images the phosphorescent screen of the image converter tube onto the film. Principal characteristics of the system are: fore-optics aperture is f/1.2, image tube cathode is 20 x 20 mm, image tube internal magnification is a factor of two, phosphor screen area is 40 x 80 mm, and camera optics aperture is f/1 with a 2:1 reduction. Electronic driving and control circuitry developed at AWRE provides framing rates as high as 2×10^7 fps with an exposure duration one fifth of the interframe time; i.e., 2×10^7 fps implies 50 nsec between frames and an exposure duration of 10 nsec. In addition, the number of frames can be adjusted to cover the entire phosphor screen area. A typical arrangement would be to give eight frames, each frame being 20 x 20 mm on the screen. Typical resolution is about 5 lp/mm at the shortest exposure times, and about 10 lp/mm for exposure times of the order of 1 μsec. The camera has also been used in streak mode, in which case the fore-optics is changed to include the streaking slit and an additional lens to re-image the slit onto the photocathode. The streaking electronics equipment allows streak rates of up to about 1.5 mm/nsec on the phosphor screen. Thus, if the light source being photographed has sufficient radiance, the time resolution achieved in streak mode can be as short as 1/15 nsec, i.e., better than 10^{-10} sec.

Three E 12 cameras with streak electronics were used by LASL in a plasma diagnostics experiment in June 1967. For this experiment, the camera part of the optics was changed so that the photograph of the phosphor screen was reduced 5:1 from the screen size. Two of the cameras were used to photograph the focal plane of an f/1 spectrograph, thus serving as streak spectrographs. In all parts of this experiment, quantitative calibrations were made to allow radiometric analysis of the experimental results.

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* See Appendix B for reprints of these references.

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Detailed descriptions of these tests, along with reproductions of the image converter camera films, have been given by Zavattaro et al.[11]

Further development work in England at John Hadland (P.I.), Ltd. has produced the Imacon, a commercial version of the AWRE E 12 camera. There are few essential differences between the E 12 and the Imacon, the most useful being that the electronic circuitry that changes the frame rate is interchangeable in the Imacon. In addition, the quality control of the image converter tubes used in the camera has been significantly improved. The Imacon uses the type P 856 tube made commercially by English Electric Valve, Ltd.

E 14. The E 14 camera is intended for very high spatial resolution photography, e.g., determination of the initial motion of the weapon case and bomb debris in the first few microseconds after detonation. The principal limitation in such photography is atmospheric "seeing," usually given as, at best, 2 sec of arc or about 1 part in 10^5; i.e., for a bomb at 100 km altitude, atmospheric seeing would probably limit spatial resolution to about 1 meter. Since very prompt bomb debris may have velocities approaching 10^9 cm/sec, the desired time resolution capability of the E 14 camera is 10^{-7} sec.

Experience with aircraft-based instruments in high altitude weapon testing has led to the rule of thumb that a well-trained crew can accurately position the aircraft at the desired time so that optical instruments with fields of view of at least 3° have a good chance of getting the desired data. Fields of view of less than 3° require tracking or automatic positioning devices. The field of view for ground-based instruments without tracking aids should be about 1°; with tracking aids readily adaptable to nuclear test instrumentation the useful field of view can probably be decreased to 1/2°. On the basis of these ideas, it was decided to design two different types of E 14 cameras. One, the 6 E 14, will have a 3° field of view with an entrance aperture not larger than 10 in. This instrument is intended for aircraft mounting. The other, the E 14 G, will have a 1/2° field of view and will require considerably more space than the 6 E 14; therefore, it is intended for ground-based use.

Schardin[12] and others[13,14] have shown that diffraction effects limit the resolution that can be realized in a rotating mirror camera. The magnitude of the effect depends on the size and rotational speed of the mirror. A simple expression given by Davis[13] shows that the total number of resolved line pairs in the frame is equal to 1600 t, where t is the exposure duration for the frame in microseconds. For the E 14 cameras this gives 160 line pairs, or, roughly, 320 lines. But the required resolution in the E 14 G is also given by the total field of view divided by the required angular resolution; i.e., 1/2° (or 1/120th of a radian) divided by $1/10^5$ (or 10^{-5}) radians per line, which gives a value of about 10^3 lines required in the frame. Thus, a rotating mirror camera cannot be made to give the resolution required for the E 14 G camera. (The principal limitation is the strength of the rotating mirror material.) Because the desired field of view for the 6 E 14 is about six times as large as that for the E 14 G, these limitations would not apply and it might be feasible to design a rotating mirror camera for aircraft-based work.

Realizing these limitations, AWRE in 1964 started to design and build an image converter tube that would provide the required resolution. The initial design goal was a tube with about 40-mm anode diameter in which the total number of resolved lines would be about 1200, with little or no variation of resolution across the total field. This work led to the development of the AWRE type FE 11 image converter tube,[10] an optical design for the E 14 G, and both mechanical and optical designs for the 6 E 14 camera.[15,*]

Each optical system consists of a telescope to image the source onto the convex photocathode of the FE 11 image tube and a camera lens with field flattener which re-images the convex anode phosphor screen of the tube onto the film. For the E 14 G, the telescope is a Gregorian design working at about f/20; for the 6 E 14, the telescope is a folded, reflecting, off-axis, Schmidt design working at f/20. Neither design has moving image devices nor moving film; a single picture is obtained from each separate image tube. The sequence and gating electronic

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*See Appendix B for reprints of these references.

circuitry is straightforward and provides a wide range of exposures and times between pictures.

The mechanical design of the E 14 G has been deferred until completion of the much more difficult 6 E 14. The 6 E 14 consists of six separate optical channels, each with its Schmidt telescope, with the entrance pupils arranged so that the envelope of the pupils fits inside a 10-in. diam circle. The instrument structure also contains an XDT-54 type photoelectric detector (designed and built by EG&G) which triggers the start of the first frame. The detector makes a very fast-rising pulse of about 10 V amplitude within 10 nsec of the time that the irradiance on the multiplier photocathode reaches a specified threshold value. This threshold can be varied by means of an adjustable aperture and lens stop in the optical system in front of the photomultiplier. The rest of the 6 E 14 includes a camera lens with 70-mm film transport for each image tube.

AWRE has built a prototype 6 E 14 camera which includes the Schmidt optical system for only one frame. Completion of this prototype requires solution of resolution problems which have arisen in the development of the FE 11 image tube. Tests show that the tube has the required resolution only for exposure durations longer than about 1 μsec. If the exposure duration is made to be, say, 1/4 μsec, the resolution decreases by about a factor of four. Further efforts will be made to solve these problems, but the outcome is uncertain. One conclusion would be to forego the 0.1 μsec requirement and settle for an exposure duration of about 1.0 μsec. Then the best solution might be a rotating mirror camera because, according to Davis'[13] analysis, an optimally designed rotating mirror camera can give 1600 lines resolution across the frame in the time direction for a 1.0-μsec exposure.

<u>E 16</u>. The E 16, another camera designed and built by AWRE, is a single frame image intensifier camera designed for use with the STL/TRW Model 1 image converter camera. The image tube is the RCA type 6914 which has an aperture of about 1 in. diam. The relay lens which re-images the image tube phosphor screen onto the 4 x 5 in. film has an f/1.2 aperture. Two instruments were made by AWRE and lent to AEC laboratories where tests show that the camera provides an exposure increase of a factor of 60. But this exposure gain is at the expense of resolution, which at best is about 5 lp/mm.

<u>E 17</u>. The E 17 camera, a modification of the E 12, provides a continuous circular sweep of the 2x magnified image of the image converter cathode. The sweep does not rotate the image about the center of the anode, rather, spatial relationships in the cathode image are preserved as the image moves along the circular path on the anode. The desired times for one revolution are 1, 10, and 100 μsec. One prototype E 17 camera with a 10-μsec, nearly circular sweep has been made by AWRE and lent to LRL for testing. The tests led to some design improvements which were incorporated into a second prototype camera now being tested at AWRE. The first camera will be returned to AWRE for modification. Future cameras of this type should probably be made in the USA using the image converter tubes now commercially available in the UK (English Electric Valve, Ltd. type P 856 Shuttering Image Tube).

<u>Spectrographs</u>

<u>SPREFS</u>. The SPREFS is a space-resolving, framing spectrograph intended for fast time resolution spectroscopy of high altitude bursts or any other source of comparable radiance in which spatial resolution is important. SPREFS is an f/3 spectrograph with 50-Å/mm dispersion, wavelength coverage from 3000 to 9000 Å on 5-in.-wide film, maximum frame rate of 10^5 fps (no dead time between frames), and about 950 frames maximum (before rewrite). Spatial resolution is obtained using a fiber optics image transformer and optical system which transforms a circular field of view into a rectangular pattern at the entrance slit of the spectrograph. The design was invented at the AWRE.[16],*

The Mk I version of SPREFS was built by AWRE to prove the optical and mechanical design concepts. This instrument was made available to LRL for tests in January 1967, and was moved to LASL for further testing in July 1967. The tests showed that the design meets specifications, and led to some improvements in the Mk II version now being built at the AWRE. The Mk II instrument will include an automatic sequencing control system to enable remote operation from a central control area where many similar

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*See Appendix B for a reprint of this reference.

timing and control operations would occur. Yet to be completed is a demonstration that the housing is strong enough to contain all the fragments should the high speed drum or rotating mirror disintegrate during a run. AWRE expects to complete and test the Mk II prototype by mid-1969; it will then be made available to USA participants for further evaluation.

Figure 1 is an AWRE cutaway drawing of the principal parts of the Mk I version (the Mk II is similar); Fig. 2 is an AWRE drawing that shows the correspondence between image transformer fibers and the film plane; and Fig. 3 is an AWRE schematic of the optical components of the spectrograph. Detailed descriptions of this instrument have been given by Waller[16] and Allison.[17]

M9. The M9 spectrograph is a high spectral resolution, optically fast spectrograph that uses crossed dispersion gratings to give 1200 Å or more wavelength coverage in a single exposure covering a 25-mm-diam circle on 35-mm film. The spatial resolution in the image is better than 4 μ; the dispersion depends on wavelength, being about 2 Å/mm at 2000 Å and about 8 Å/mm at 8000 Å. Thus, the spectral resolution varies from about 0.008 Å at 2000 Å to about 0.03 Å at 8000 Å. The geometrical aperture of the spectrograph is f/2, but the vertically dispersing grating and the convex mirror of the camera cause a 40% central obscuration so that the effective aperture is about f/3. Figure 4 is a plan view optical schematic of the instrument, and Fig. 5 is an enlargement of a typical spectrogram. The M9 spectrograph can be made into a framing spectrograph by using a rotating slotted disk just in front of the entrance slit along with a transport mechanism that moves film through the film plane. To avoid overlapping orders in the spectrogram, the ratio of time between frames to exposure duration of a single frame must be greater than about 300. Equipment of this type has been made which allows exposure durations as short as about 5 μsec.

The M9 spectrograph was designed and built by C. J. Silvernail at the Regulus Co. in San Diego, Calif. Two instruments were built (one is at LASL and the other is DASA property consigned to EG&G, Inc., Bedford, Mass.) before the Regulus Co. was purchased by E. H. Plesset Co., an EG&G subsidiary. Future availability of the M9 is uncertain.

Other Instruments

In addition to cameras and spectrographs the Subwog has been involved in the development of other optical instruments, namely, an airborne scanning Fabry-Perot interferometer, a grazing incidence grating spectrograph for x rays in the 0.3- to 50-Å wavelength range, a near-infrared spectrograph, and an optically-fast scanning monochromator.

Airborne Scanning Fabry-Perot Interferometer. Optical diagnostic studies of the late-time debris in high altitude nuclear explosions require an instrument with high spectral resolution (typically about 0.01 Å), high sensitivity, and a wavelength scanning mechanism. These requirements can be satisfied best by interferometers, but it is very difficult to make a scanning interferometer sufficiently rugged and rigid to operate in the vibrating environment of a jet aircraft. Considerable work has been done at AWRE in developing a vibration-resistant, scanning Fabry-Perot interferometer of 1-in. aperture that can be scanned at rates from about 10 msec to as slow as 100 sec for one order. Two different scanning mechanisms were used, piezoelectric and magnetostrictive. Tests of prototypes of both designs showed that the vibration problems could be solved; the interferometer retains its high resolution when subjected to the vibration in a jet aircraft flying at 30,000 to 40,000 ft. However, the magnetostrictive design was unsatisfactory in that the center wavelength drifted if the instrument was operated for more than a few minutes. This drift is almost certainly due to thermal expansion of the spacers. The piezoelectric design had an undesirable torsional resonance. Although the initial designs failed to meet specifications for airborne operation, the instruments are still of interest because they are considerably more stable than other scanning Fabry-Perot interferometer designs.

A second design now being built at AWRE incorporates the best features of both earlier designs in a 2-in.-aperture instrument. This one will be piezoelectric scanning in a very rigid mount similar to that used on the first magnetostrictive design. This new design will be tested by AWRE in March 1969 in an experiment intended to measure the shape of

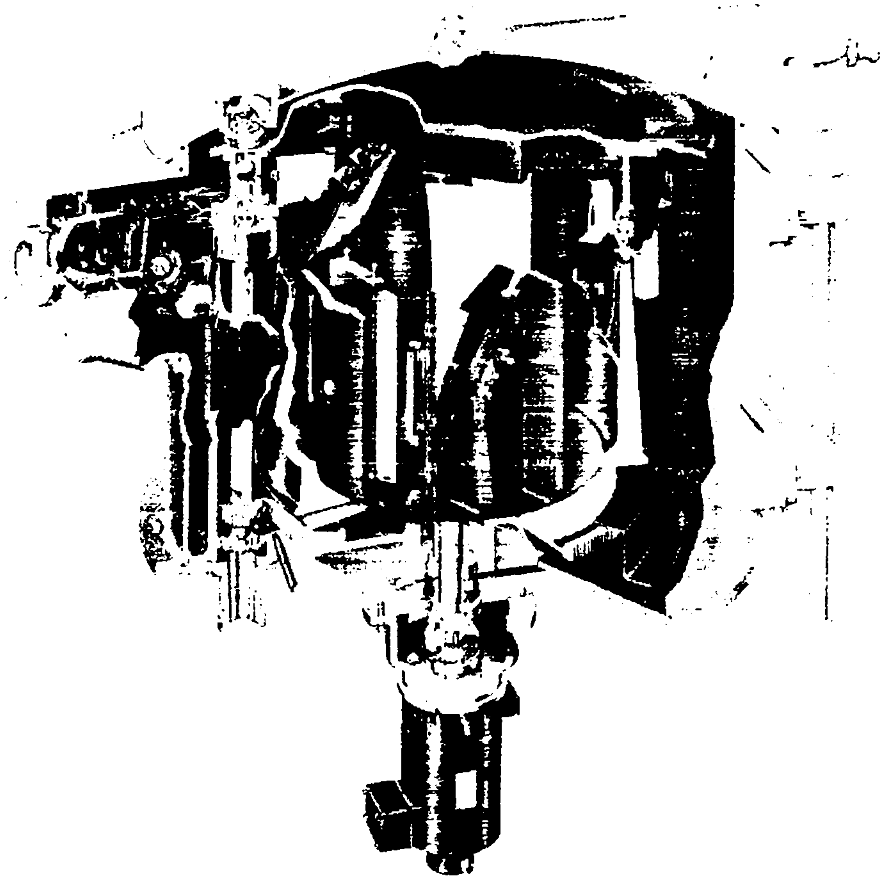

Fig. 1. SPREFS Mk I (AWRE drawing).

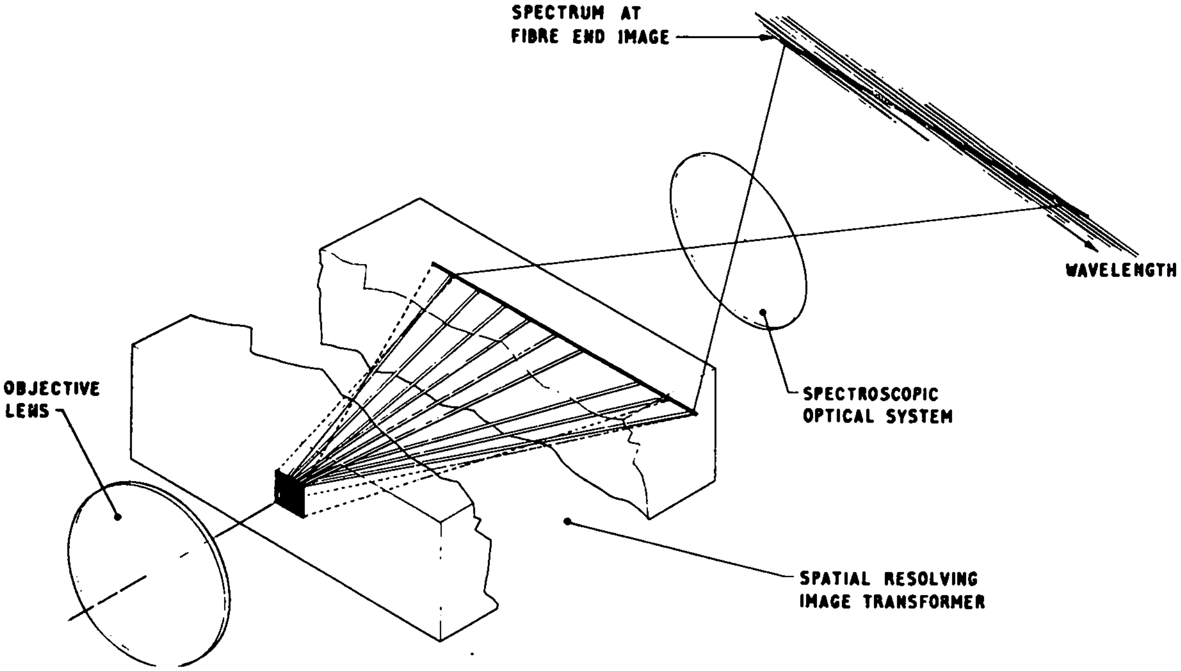

Fig. 2. SPREFS image transformer.

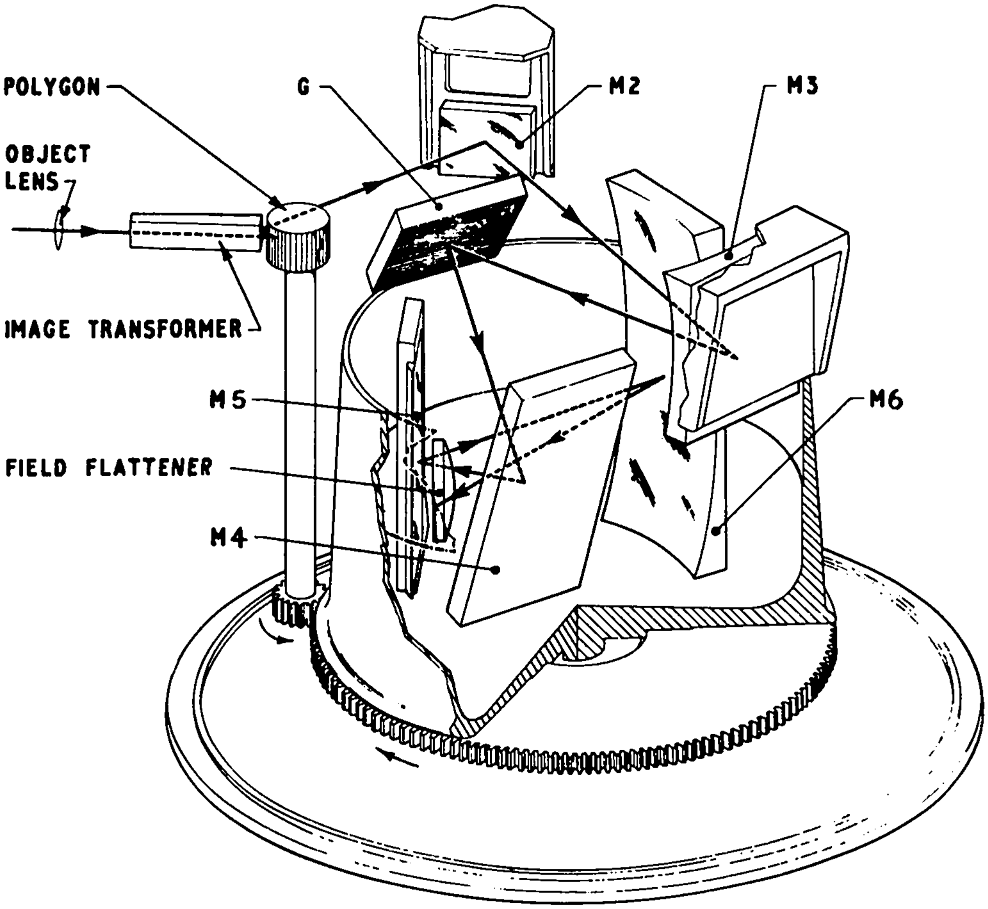

Fig. 3. SPREFS optical system.

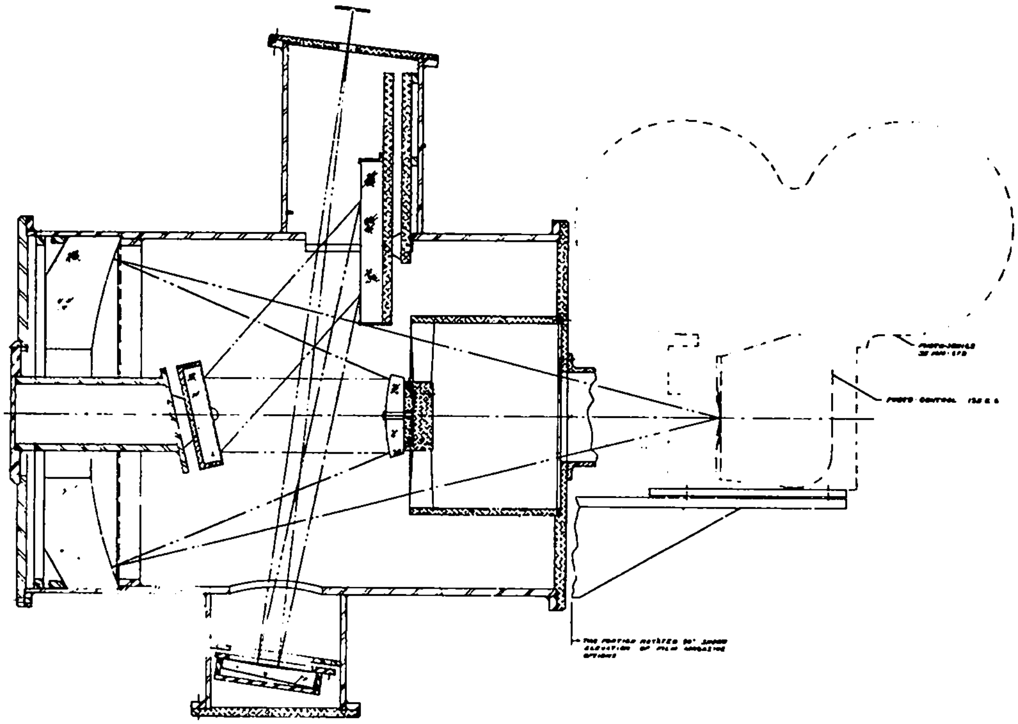

Fig. 4. M9 spectrograph layout.

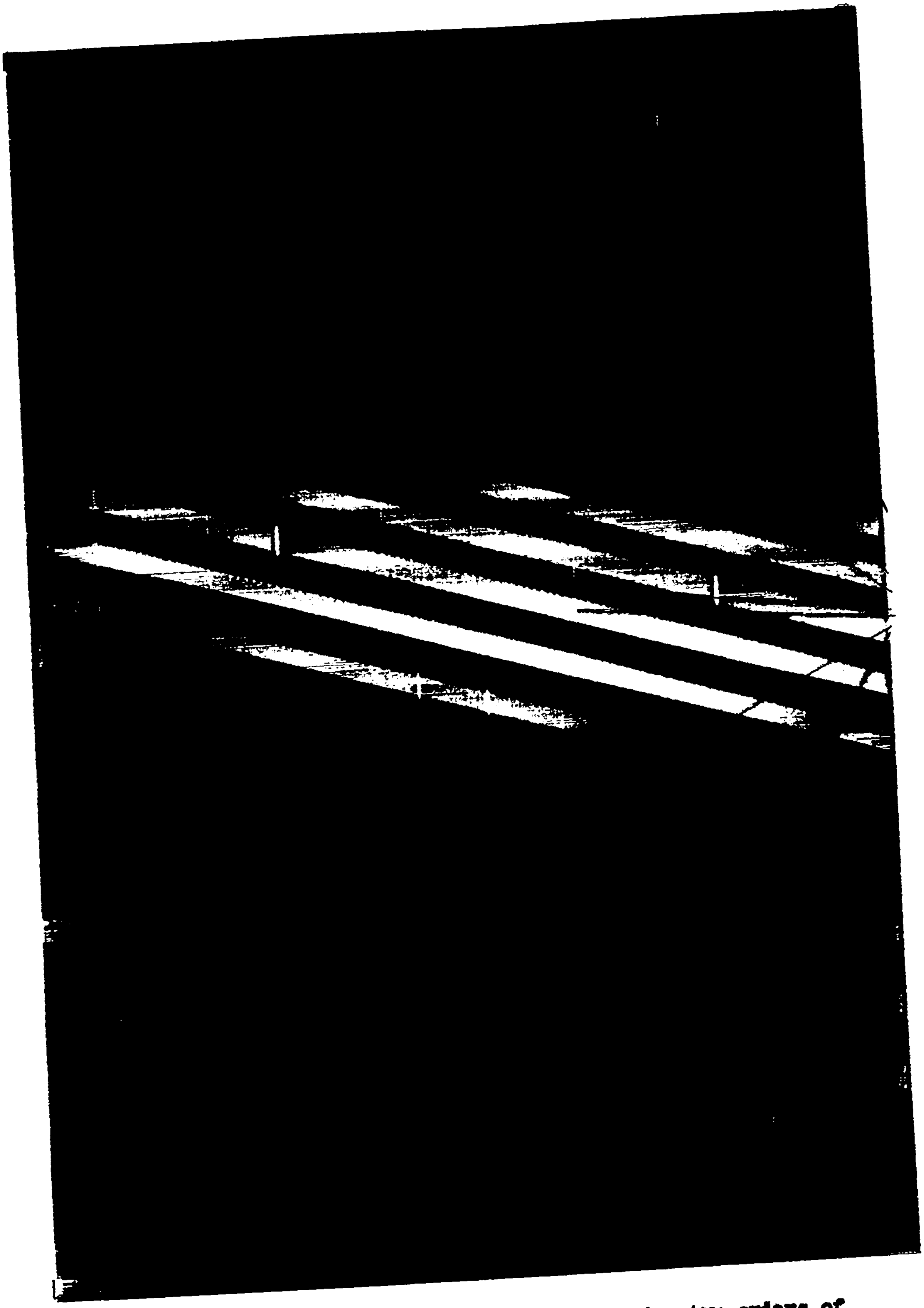

Fig. 5. M9 spectrogram of fluorescent lamp, showing two orders of principal lines and some evidence of grating ghosts.

resonance lines of Ba$^+$ produced in a high altitude chemical release. If this design proves successful, further work will be done to develop scanning interferometers of 3- to 5-in. aperture.

X-Ray Grating Spectrograph. The AWRE, in cooperation with the UK National Physical Laboratory (NPL) and the UK AERE at Harwell, have designed and built a photographically recording, grazing incidence, concave grating spectrograph for use in the 0.3- to 50-Å wavelength range. The unique characteristic of the gratings, made by a special process at NPL, is that they successfully diffract photons of such short wavelength. This is in contrast to any similar gratings made by others, which do little but scatter wavelengths less than about 5 Å. Other characteristics of the spectrograph are: concave grating radius of curvature, 5.0 m; Rowland circle radius of instrument, 2.5 m; angle of incidence either 10, 20, or 40 min of arc from grazing; and grating ruling frequency, 300 lines/mm. Because of the optical properties of concave gratings, the size of the instrument is considerably less than one might suppose from the grating radius: the finished instrument is about 4 x 6 x 18 in., exclusive of the vacuum pumping system. Early results obtained with such gratings have been discussed by Franks and Lindsey.[18] Additional work by Speer[19] shows that the resolution at 5 Å varies from about 0.05 to about 0.1 Å depending on the thickness of film emulsion used. The effective aperture of the instrument is about f/1000. The measured grating efficiency is about 10%, and agrees well with expectation based on scalar diffraction theory.

AWRE is now building four such instruments, two of which will be lent to LASL and LRL early in 1969. Both instruments will have photographic film detectors, but this limitation is expected to be removed when an AWRE-designed photoelectric detector mount becomes available. This detector mount will allow placement of up to 12 separate solid state chips along the Rowland focal surface.

Because the NPL gratings are very scarce, one condition imposed on use of the instruments lent by AWRE is that the spectrographs must be used so as to preclude damage to the grating. This restriction will limit weapons test applications, but there are many alternative uses of such a unique instrument, such as laboratory calibrations of x-ray detectors and fluors. A larger supply of gratings may become available as a result of a contract between the Imperial College, London, and Hilger and Watts. This contract, made in October 1968, calls for the manufacture of 30 gratings during the subsequent year. If the 30 gratings are made, it may be possible to develop rocket-borne x-ray grating spectrometers that would be valuable in high altitude weapons testing.

Near-Infrared Spectrograph. Many important aspects of late time, high altitude debris motion are best studied by measurements of the infrared emission from the debris and excited air. Spectrographs suitable for field use are restricted to wavelengths shorter than about 8000 Å by the lack of sensitivity of photographic films. Films are available that have some sensitivity to light of wavelengths as long as about 1 μ, but they are very special emulsions that require so much special handling as to make them essentially unusable in field work. Therefore, the Subwog has investigated the possibility of designing an optically fast spectrograph which would use red/infrared-sensitive image intensifier tubes to overcome the sensitivity problems. Initial specifications developed by DASA are:

Wavelength range, 7500 to 11,000 Å

Free spectral range, 1500 Å (i.e., the wavelength range covered in a single exposure)

Spectral resolution, 1 Å or better

Geometrical aperture, f/10

Effective aperture, including exposure gain from intensifier, f/2

Slit height, 10 mm in a stigmatic design such that spatial resolution in the source is achieved along the slit

Film width, 70 mm

Time resolution (time to cover the wavelength range of 1500 Å), variable from 1/50 to 1.0 sec

Considerable design work at EG&G (under DASA contract) and at AWRE led to the conclusion that these specifications could not be satisfied by any image intensifier tubes for which accurate performance data could be found. This conclusion has to be vague because much of the work on red/infrared image tubes is highly classified, sensitive, military defense work, and we have not been able to obtain accurate data on the performance of some tubes being developed for military purposes. Consequently, other designs are being studied which, although they may not meet all of the DASA specifications, may lead to an instrument that is very close to meeting most of them. One such design was presented by AWRE at the seventh Subwog meeting in October 1968. The resulting discussion led to questions about the assumed sensitivities of film and photodetectors which must be resolved before work can proceed.

Scanning Monochromator. Relatively few detailed spectroscopic data are available on the time dependence of emission from late time debris and debris-air mixtures resulting from high altitude nuclear tests. An instrument is required which can cover relatively large wavelength ranges with good spectral resolution, and which has good sensitivity. Interferometers are not always suitable because the wavelengths of many lines of interest are not known, a priori, to lie within the free spectral range of the instrument. Spectrographs can have the wavelength coverage, but the photographic film severely limits the sensitivity. Accordingly, an optically fast, scanning monochromator with high dispersion is required. Original specifications of such an instrument, discussed at the fourth Subwog meeting are:

Aperture, f/1 or better

Dispersion, 5 Å/mm

Wavelength range, 2000 to 9000 Å, selectable by grating change to attain maximum light flux efficiency

Scan speed, 1 Å/msec to 1 Å/min

Slit height, 2 in. minimum

Detectors, S-1, S-19, and S-20 photomultipliers in interchangeable mounts

The consensus of the Subwog is that all of these specifications cannot be met with existing technology. The best available design, discussed by W. Waller of AWRE at the seventh Subwog meeting, is based on a design by Hulthen and Lind[20] in which a plane mirror is used with a plane grating so as to return the once-diffracted light to the grating, thus doubling the dispersion. Scanning is also arranged to maintain use of the grating at blaze by coupling the rotations of the mirror and grating. The AWRE design would use a grating of 8 x 10 in. ruled area with a camera optical system of 8-in. focal length, giving f/1 aperture; but, with the gratings available, the dispersion attained is only 18 Å/mm. The design allows for simple interchange of camera mirrors so that the dispersion is changed to 5 Å/mm by changing the aperture to f/3. This design is being studied further at AWRE and will be discussed later this year.

Summary

A brief summary of the status (in January 1969) of the instrument developments discussed is as follows.

1. Model 739 Camera: continuous writing, rotating mirror framing camera, achromatic over 3000- to 9000-Å wavelength range, frame rates up to about 3×10^5 fps with a few microsecond exposure duration; preliminary design is a modification of Brixner's[6] Model 7 camera; achromatic optical design being done at AWRE and at LASL; mechanical design under way at IRL where prototype instrument will be built; present schedule calls for prototype to be finished late in 1969.
2. Slow All-Sky Camera: f/1 aperture, 70-mm film, 165° field of view; camera (Model PAX-71) is being built by Pacific Optical Co. under contract to EG&G, Inc., Bedford; delivery expected by July 1969.
3. Fast All-Sky Camera: must give frame rates up to about 1000 fps on 70-mm film; AWRE is testing a possible lens design with large enough back focal distance to allow for fast imaging and a film transport mechanism.
4. E 12 Image Converter Camera: very fast, framing or streak, framing capability is 8 to 10 frames with exposure as short as 10 nsec, streak capability is 4 x 8 cm picture at streak rate as fast as 1.5 mm/nsec, image resolution at film is 5 line pairs/mm; cameras are available commercially (trade name Imacon) from John Hadland (P.I.), Ltd, Bovingdon, Herts, England.
5. E 14 Image Converter Camera: very high spatial resolution, exposure duration as short as 0.1 μsec; ground-based version has resolution limited only by atmospheric seeing; airborne

version has resolution about 1/6th of ground version; AWRE has built single frame prototype of airborne version called 6 E 14; ground version is designed; AWRE-designed FE 11 image converter tube does not give required resolution for exposure times less than 0.5 μsec; considerable doubt about final success in attaining 0.1-μsec exposures.

6. E 16 Image Intensifier Camera: f/1.2, uses RCA 6914 image tube, 1.0-in.-diam cathode, 0.86-in. anode, gives exposure gain of about 60; AWRE has built two cameras which are on long term loan to LRL and Sandia Corp.

7. E 17 Image Converter Camera: continuous writing, circular-streak camera with sweep times of 1 to 40 μsec per revolution; AWRE has built two prototype cameras, one on loan to LRL; LRL and AWRE are making tests; E 17 uses the same image converter tube as the E 12/Imacon; future supply of E 17 cameras will be made by user; P 856 image tube is sold by English Electric Valve, Ltd.

8. SPREFS: space resolving, fast framing spectrograph, f/3, 50 Å/mm, 3000 to 9000 Å coverage on 5-in. film, maximum frame rate is 10^5 fps with no dead time between frames, total number of frames is 950, space resolution achieved by means of fiber optics image transformer with 100 elements: AWRE designed and built Mk I version to test mechanical and optical design concepts; Mk II final version with automatic sequence control system will be finished in the first half of 1969, and will be lent by AWRE to USA Subwog participants.

9. M9 Spectrograph: f/2, 2 to 8 Å/mm, 0.01- to 0.1-Å resolution, wavelength coverage at least 1200 Å at any wavelength in the range 2000 to 9000 Å, image is 25 mm diam on 35-mm film, framing accessory available to give few microsecond exposures with a few milliseconds between frames; two M9s built by Regulus Co., one is at LASL, the other is DASA property consigned to EG&G.

10. Scanning Fabry-Perot Interferometer: rigid mount needed for use in jet aircraft, scanning rates from 0.01 to 100 sec per order, different sizes needed--from 1- to 5-in. aperture: AWRE has designed, built, and tested two prototypes, one using piezoelectric scanning and the other magnetostrictive; test results led to design of 2-in.-aperture piezoelectric instrument which will be tested in March 1969 during high altitude Ba release experiments.

11. X-Ray Grating Spectrograph: succeeds in diffracting x rays of wavelengths as short as 0.3 Å, usable range is 0.3 to 50 Å, effective aperture is f/1000, photographic film is used as detector; AWRE is building four instruments; one will be lent to LASL and one to LRL during spring of 1969; gratings are very scarce; future supply depends on success of Hilger and Watts in learning manufacturing process from the UK National Physical Laboratory.

12. Near-Infrared Spectrograph: f/10 geometric aperture with image intensification to give effective f/2 aperture, resolution to be 1 Å or better, wavelength range 7500 to 11,000 Å; AWRE has tentative design, but lack of accurate information about suitable infrared image intensifiers makes success doubtful.

13. Scanning Monochromator: f/1, 5 Å/mm, wavelength range 2000 to 9000 Å, scan speeds 1 Å/msec to 1 Å/min; best design is being studied at AWRE; not all specifications can be met, e.g. can get f/1 at 18 Å/mm or 5 Å/mm at f/3.

FUTURE SUBWOG WORK

The instrument development work already described is a sizable program which will take another year or two to complete. However, there are other high altitude test objectives for which little or no instrument development work is being done. For example, there seems to be no work under way to develop field instrumentation for soft x ray measurements, and there remain many rocket instrument and technology problems in developing ultraviolet and vacuum ultraviolet capability. It is doubtful that the Subwog will participate in any of this rocket work because of the added difficulties in coordinating among many laboratories what is really vacuum ultraviolet optical physics research. Furthermore, the interface problems of mating instrument payloads to

[redacted]

rocket assemblies require so much coordination of experimenters with rocket engineers as to preclude involvement of more than one or two laboratories.

In addition to the design and construction aspects of instrument development work there has been, and will continue to be, considerable effort involved in adequate testing of the finished instruments. It seems clear from a scientific point of view that the testing should be incorporated into some experiments that will provide not only an assessment of the instrument performance but, more important, will also produce results which are needed to increase our understanding of the many difficult physics problems of high altitude weapons effects. Many such experiments are difficult and complex and may require a cooperative effort from several of the laboratories; such efforts may well become the principal function of the Subwog within a few years.

ACKNOWLEDGMENTS

The author appreciates the interest and encouragement expressed by Herman Hoerlin of LASL and Iauen Maddock, formerly of AWRE, in forming the Subwog. The excellent work by the staff of the AWRE Optics Group, led by Kenneth R. Coleman, is gratefully acknowledged; without them this work could not have been done.

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APPENDIX A

SUBWOG MEETINGS AND MEMBERSHIP

Subwog Meeting Dates and Places

First	AWRE, Aldermaston	April 21,22, 1964
Second	LASL, Los Alamos	September 14,15, 1964
Third	AWRE, Aldermaston	July 20-22, 1965
Fourth	LRL, Livermore	May 24-26, 1966
Fifth	AWRE, Aldermaston	March 14-17, 1967
Sixth	LASL, Los Alamos Sandia Corp., Albuquerque	February 8,9, 1968 March 19-21, 1968
Seventh	AWRE, Aldermaston	October 8-10, 1968

Subwog Membership

LASL	H. Milton Peek, Chairman
LRL	Erwin C. Woodward
Sandia	James M. Hoffman M. A. Palmer, Alternate
DASA	Lt. Col. H. Carl Fitz, DASA HQ John Rex, AFCRL, Alternate Donald F. Hansen, EG&G, DASA Optical Contractor
AWRE	Kenneth R. Coleman C. D. Reid R. J. Rout A. Skinner W. A. Waller

APPENDIX B

REPRINTS OF PUBLICATIONS ON AWRE CAMERA DEVELOPMENT

B-1

A. E. Huston, "Some New High Speed Cameras," reprinted, by permission, from J. Photog. Sci. 14, 251 (1966); describes work by AWRE in developing the E 12 and E 14 cameras.

Some New High-Speed Cameras

A. E. HUSTON
A.W.R.E., Aldermaston, Berks.*

ABSTRACT. By exploiting the possibilities of image converter tubes, some new high speed cameras have been developed having advanced performance. These include a simple single frame camera with an exposure time of 20 nS, a single-frame camera of high resolution and wide spectral range, a streak camera capable of writing speeds up to 4000mm/μs., and a framing camera which can operate at speeds from 10^5 frames/sec. to $6 \cdot 10^7$ frames/sec. The basic electrical circuits used in these cameras are described, together with details of their performance.

INTRODUCTION

In many branches of scientific investigation, photography can be a powerful measuring tool. It is possible to contain a very large amount of information in a single photographic record, and, furthermore, this information can usually be obtained with little or no disturbance to the experiment under investigation. The need to examine very rapid processes has led to the establishment of a specialised technology viz. high-speed photography, and a large proportion of the effort in this field has been devoted to the development of a wide range of high-speed cameras.

Most high-speed cameras are entirely mechanical-optical in their method of operation. Such cameras employ film transport mechanisms giving either intermittent or continuous motion, or have a stationary film with a rotating mirror. Most applications requiring the use of high-speed cameras are adequately dealt with by mechanical-optical types, but there are some fields in which apparatus of this description exhibits serious shortcomings; these are:–

1. Where single exposures of very short duration are required.
2. For framing speeds above about 10^7 per second, where aperture and resolution of mechanical cameras have to be sacrificed to obtain high time resolution.
3. For framing speeds in the region of 10^5 per second, which are unattainable by continuous-motion film cameras, and require rotating mirror cameras which, in this speed range, are either inefficient or unduly large and expensive.
4. Low-light-level applications, where high effective aperture is essential.
5. Applications where a triggered camera, rather than a continuously-running one is required e.g., in projectile photography.

The author has, for some years, been engaged on the development of the electronic image tube as the active component in high-speed cameras, and this device enables cameras which meet the above requirements to be designed. A major advantage of the image tube in this application is its versatility, since the electron beam may be:—

1. Switched on and off rapidly to act as a shutter.
2. Switched repetitively, and deflected in discrete steps, forming a framing camera.
3. Deflected continuously across the screen to form a streak camera.

The efforts made, in the author's laboratory, to exploit these features, have resulted in the development of a number of single-frame, framing and streak cameras, and this article describes the present state of these developments.

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*Present address: John Hadland, (P.I.) Ltd., Newhouse Laboratories, Bovingdon, Herts.

MS. received 28 December 1965.

The Journal of Photographic Science, Vol. 14, 1966

THE IMAGE TUBE AS A SHUTTER

The requirement is simply that the electron beam in the tube be allowed to proceed from photocathode to screen only for the duration of the exposure desired. Some tubes designed for shutter operation include special electrodes intended to act as gating points. in fact making the tube into a triode. With such tubes it is possible to gate the electron beam with a pulse of amplitude, say, 250 volts, but there is considerable disadvantage in that a pulse of almost ideal shape is essential (i.e., the rise and fall times of the pulse must be very small compared with the total duration and the top of the pulse must be flat to a high degree of accuracy). This necessity arises because, for a given anode voltage, the tube is in correct focus for one value only of the gating electrode voltage. A similar problem arises in the gating of magnetically-focussed tubes, where, for a given strength of magnetic field, a specific E.H.T. voltage is required to give correct focus.

The problem of producing idealized pulse shapes becomes increasingly difficult as pulse durations become shorter, and at A.W.R.E., an alternative technique has been adopted viz. to apply the whole tube potential in the form of a pulse. The tube in this case operates as a diode. It is necessary of course to generate a pulse of some 15-20kV, but pulse shape is relatively unimportant since diode tubes may be designed to maintain focus over a wide range of applied voltage[1].

It is extremely important, in focussed image tubes used under pulse conditions, that the photocathode is of high electrical conductivity. In order to obtain sufficient light output from the tube to give a recordable image on the film, it is necessary to bombard the screen with a sufficient number of electrons, this number being substantially constant regardless of exposure time. The shorter the exposure, however, the greater is the current associated with this number of electrons and for exposures in the region of 10 nanoseconds might be as high as 100 milliamps. If the conductivity of the photocathode is inadequate, a current of this magnitude causes local variations of cathode surface potential which leads to distortion of the electron optics of the tube, in turn leading to poor resolution and geometrical distortion of the image on the screen. Experience has shown that a transparent conducting substrate, with a resistivity of less than 50 ohms, measured from centre to edge of the photocathode, is highly desirable.

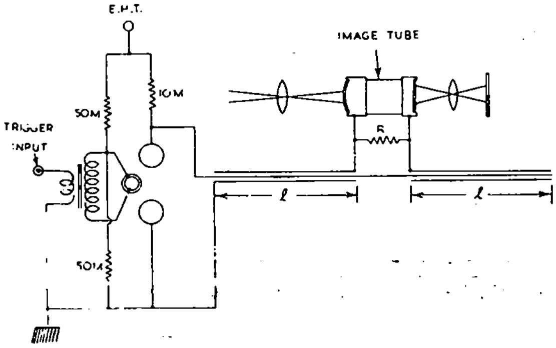

Fig. 1. Scheme of single-frame camera.

THE SINGLE-FRAME CAMERA

Fig. 1 shows the scheme of a single-frame camera using a diode image tube. The technique for generating the high-voltage pulse is very simple, consisting of a co-axial cable and a triggered spark gap. The pulse is of amplitude equal to the E.H.T. supply line, and its duration is determined by the cable length. The resistor R is made equal to twice the characteristic impedance of the cable. The switch is a corona-triggered spark gap[2] and has proved to be very reliable in practice. In the form shown in fig. 1 a trigger pulse of 200 volts, of either polarity, fires the switch with the 5/1 step-up pusle transformer shown. In a more sophisticated design, a 1/1 pulse transformer is used with a 2-stage amplifier, permitting the switch to be fired from a 10 volt pulse, the total triggering delay being 65nS and the jitter time +2nS.

A number of cameras of this type have been built using the 6929 image tube*. This tube has a spherical photocathode surface and a plane screen. Towards the edge of the field the resolution deteriorates seriously, and a considerable degree of pin-cushion distortion is evident. These effects are aggravated if a standard photographic lens is used for the objective. The simplest solution is to restrict the area of photocathode actually used to about 10 mm diameter. Under these circumstances there is very little pin-cushion distortion, and loss of resolution at the edge of the field is slight. It is also possible to employ standard objective lenses as the spherical image surface can be accommodated over this small area. The resolution per frame width, under pulse conditions, is the order of 200-250 line pairs. Fig. 2 shows records of resolution charts (a) the static

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*Manufactured by R.C.A. and Mullard Ltd.

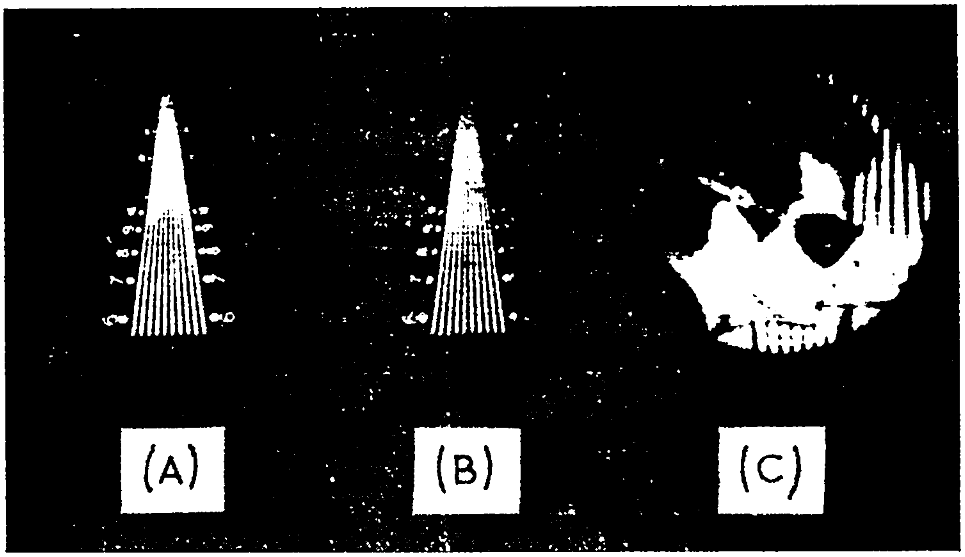

Fig. 2. Static and 30nS exposures taken with single-frame camera.

resolution about 35 line pairs/mm, (b) the resolution when pulsed for 30ns duration, about 22 line pairs/mm, (c) an image, obtained with ruby laser illumination, at 30ns exposure time. In this camera the image was relayed from the tube screen to the film by a pair of Canon 50 mm *f*/1·2 lenses, mounted face to face. The objective lens used was an Isco Westagon 50 mm *f*/1.9.

The 6929 tube is normally manufactured with an S.1 photocathode and this was in fact the type used to obtain record 2(c), as the S.1 cathode has good sensitivity at the ruby laser wavelength. The S.11 photocathode is more generally useful, and Mullard Ltd. have supplied samples of the 6929 tube with S.11 photocathodes deposited on highly conducting substrates.

In the image tube there is an effective light amplification, in terms of photons emitted from the screen compared with photons arriving at the photocathode, of about 50 times. A large portion of this is lost due to the relay optics, and in the case of the camera just described, the photon gain from cathode to film is about 5 times. The overall effective aperture of the camera, using the *f*/1·9 objective lens, is therefore about *f*/0·85.

A HIGH-RESOLUTION SINGLE-FRAME CAMERA

For some purposes a much higher order of spatial resolution is required than is possible with the design of camera just described. One application requires a resolution of 1,200 line pairs per frame width with spectral sensitivity down to 3,000Å. This specification has been met in the E.14 camera, which is shown in fig. 3 in diagrammatic form. In order to meet the resolution requirement, the image tube, type FE.11, has spherical cathode and screen surfaces. This has necessitated special optical systems to match these curvatures, and their design has been discussed by Reid[8]. The objective system is entirely reflecting, as it is required to be achromatic down to 3,000Å. It consists of two Schmidt systems in series, on the common axis indicated, and forms an image on the end window of the image tube, which has a radius of curvature of 44mm. The field diameter at the cathode is 30mm. The tube magnification is unity and the screen radius of curvature is 39mm. The copying system consists of a Dallmeyer Rareac *f*/2 unity magnification lens, the image field curvature being corrected by a fibre optic plate as shown. Initial samples of the FE.11 tube have an S.11 photo-

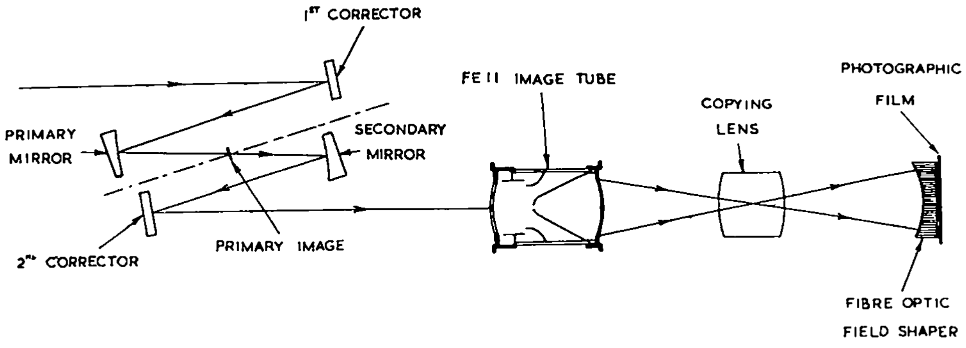

Fig. 3. Scheme of E.14 camera.

cathode, on a tin oxide conducting substrate, and the tube is now being manufactured with a cathode window of Corning 9741 glass, and a metallic conducting substrate, replacing the tin oxide, in order to extend the spectral range down to 3,000Å.

In the E.14 the effective photon gain from photocathode to film is about unity, so that the overall camera aperture is equal to that of the objective system. This is given by the relationship:—

$$f/\text{No.} = \tfrac{1}{4} \times \text{Focal length in cms.}$$

The particular model at present under development has an objective of 80cm focal length and its aperture is therefore $f/20$.

MULTI-CHANNEL CAMERAS

A series of single-frame cameras as described above may be operated in sequence to form, in effect, a kine camera. An advantage of this technique is that each exposure, and the interval between exposures, may be independently adjusted, but, on the other hand, the separate channels have different lines of sight to the event being photographed. (This may be avoided, if necessary, by the use of a beam-splitting objective system). The multi-channel camera is particularly advantageous if images of high resolution are required, as each channel may be designed efficiently without, for example, the necessity for packing several images on the screen of one tube, with consequent limitation of the available resolution.

Six E.14 single-frame camera units, for example are being built into a single system, entitled the 6E14 camera. All the electronic pulse circuitry is housed within the camera body, and arrangements have been made for the exposure duration to be adjustable in steps from 50nS to 300nS, on each channel independently. A separate programming unit supplies adjustable trigger pulses to enable the individual channels to be triggered as required.

A SINGLE-TUBE FRAMING CAMERA

In order to operate a single image tube as a framing camera, it is necessary to:—

1. Switch the electron beam in the tube on and off repetitively at the appropriate times to give the required shutter action.
2. Deflect the electron beam, suitably synchronized to the shutter action, to a sequence of stationary positions on the screen.

A special image tube has been developed for this purpose[4], and a recent development, known as the FE9A, is now commercially available.* A new method of operating the tube as a framing camera has been devised[5,6], and the principle is shown diagrammatically in Fig. 4.

The image tube has three pairs of deflector plates in the electron drift space between anode and screen.

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*From 20th Century Electronics Ltd.

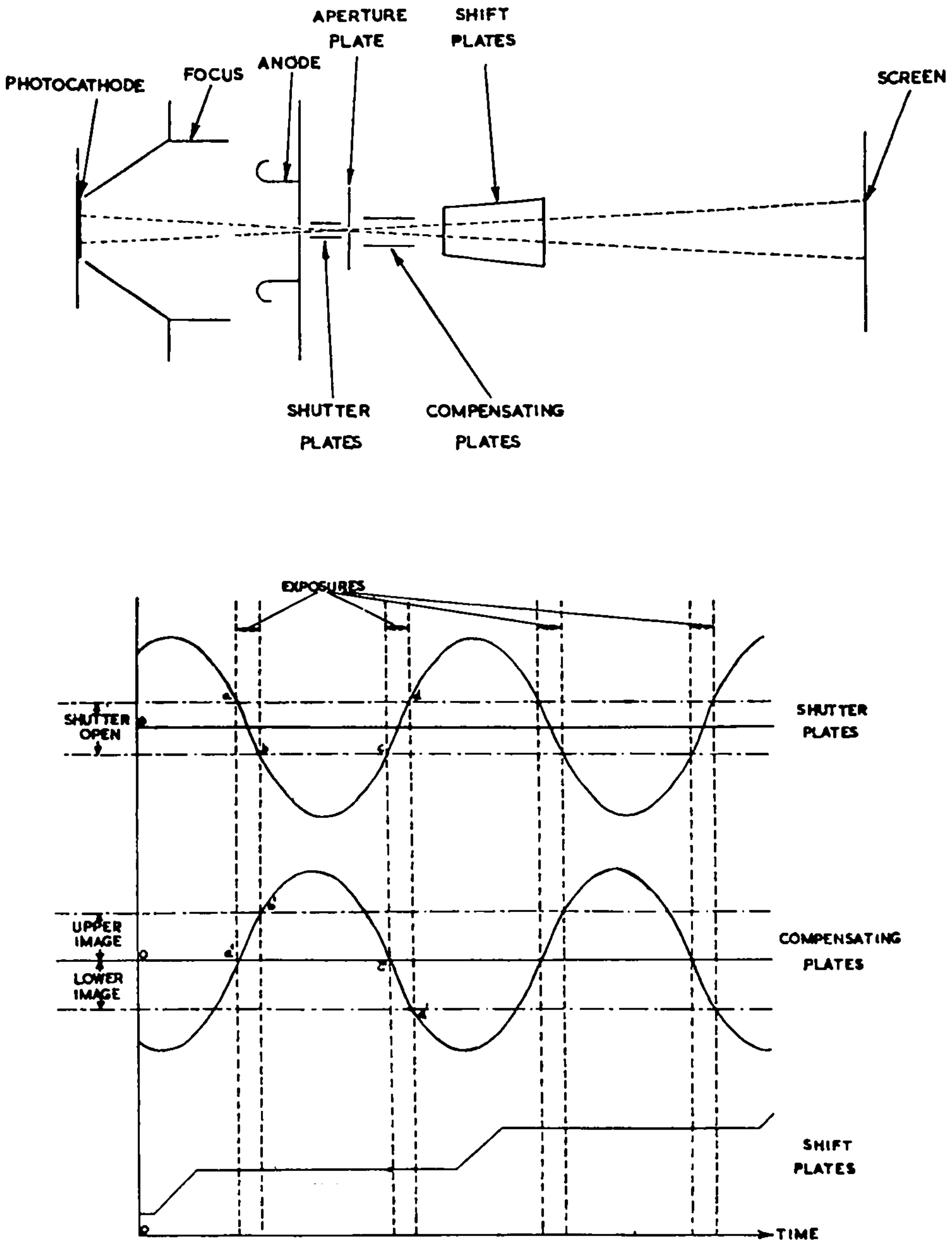

Fig. 4. Principle of operation of image-tube framing camera.

Table I

No.	*Frames/sec.*	*Exposure time*	*No. of images*	*Size of images (mms)*	*Resolution ep./frame*
1	$6 \cdot 10^7$	3nS	6 12	6×6 6×3	30×30 30×15
2	$2 \cdot 10^7$	10nS	8 16	15×15 15× 7½	60×60 60×30
3	10^6	0·2μS	10	14×14	200×200
4	$2 \cdot 10^6$ 10^5 $5 \cdot 10^4$	1·0μS 2·0μS 4·0μS	8 16 24	16×16 16× 8 16× 6	200×200 200×100 200× 80

These have been designated shutter plates, compensating plates, and shift plates reading from anode to screen, the titles indicating their function. A sinusoidal oscillation is applied to the shutter plates and this sweeps the electron beam over an aperture in a fixed plate, giving the desired effect of repetitive shuttering. Exposures are obtained when the sinusoid passes through its zero point, i.e., there are two exposures per cycle. During the "open" period of the shutter, the image appearing on the screen is moving, and, to correct for this, the compensating plates are employed. A second sinusoid, of the same frequency and amplitude but of different phase, is applied to the compensating plates. The effect is to cancel out the motion imparted to the electron beam by the shutter plates, but, by correct choice of the phase difference, alternate exposures are immobilized by different parts of the compensating plates waveform, and appear at different positions on the screen of the tube. In Fig. 4, the exposure given by a b is compensated for by a′b′, and the exposure cd by c′d′. The mean potentials of a′b′ and c′d′ are equal but of opposite polarity, so that images appear on the screen alternately one above the other. The immobilization of the images is not perfect, since the shapes of the sections of waveform a′b′ and c′d′ are not exact replicas of the sections ab and cd, but it is found to be sufficiently accurate provided the exposure duration does not exceed one fifth of the interval between frames.

The oscillations necessary for the shutter operation are generated by a valve oscillator, which is allowed to run continuously, so that if nothing further were done, there would appear on the screen two images, each of which consists of a continuous train of superimposed exposures. In order to separate them into a single sequence of discrete images, it is necessary to deflect the electron beam in a direction perpendicular to that caused by the shutter deflections.

The third pair of deflector plates, the shift plates, enables this separation to be carried out. A staircase waveform is applied, synchronized so that the "steps" of the staircase occur between exposures, and the "plateaux" are of sufficient duration to allow two exposures to be completed before the next step. A shift bias maintains sufficient deflection to keep the electron beam just off the edge of the tube screen, until a trigger pulse from the event arrives, when the staircase waveform generator starts to operate. The staircase is driven directly from the shutter oscillation, a technique which ensures the correct phase relationship.

When the sequence of images is completed, the E.H.T. supply to the image tube (20,000 volts) is rapidly removed by triggering a spark gap switch which effectively short-circuits the high voltage line. This ensures that, if the event under investigation is still highly luminous after the last frame has been recorded, there will be no further excitation of the image tube phosphor.

There is no difficult problem in coupling optical systems to the FE9A tube, since both photocathode and screen have plane surfaces. Standard photographic objectives may be used to form the primary image on the 15mm dia. photocathode, and the images on the screen, which cover an area roughly 80mm by 40mm, are relayed to the final film plane by means of a Dallmeyer Octac *f*/1·5 80mm focal length copying lens. The latter is used at unity magnification, so that its effective aperture is *f*/3. The effective photon gain from photocathode to film is about unity, so that the overall camera aperture can be stated as that of the objective lens used.

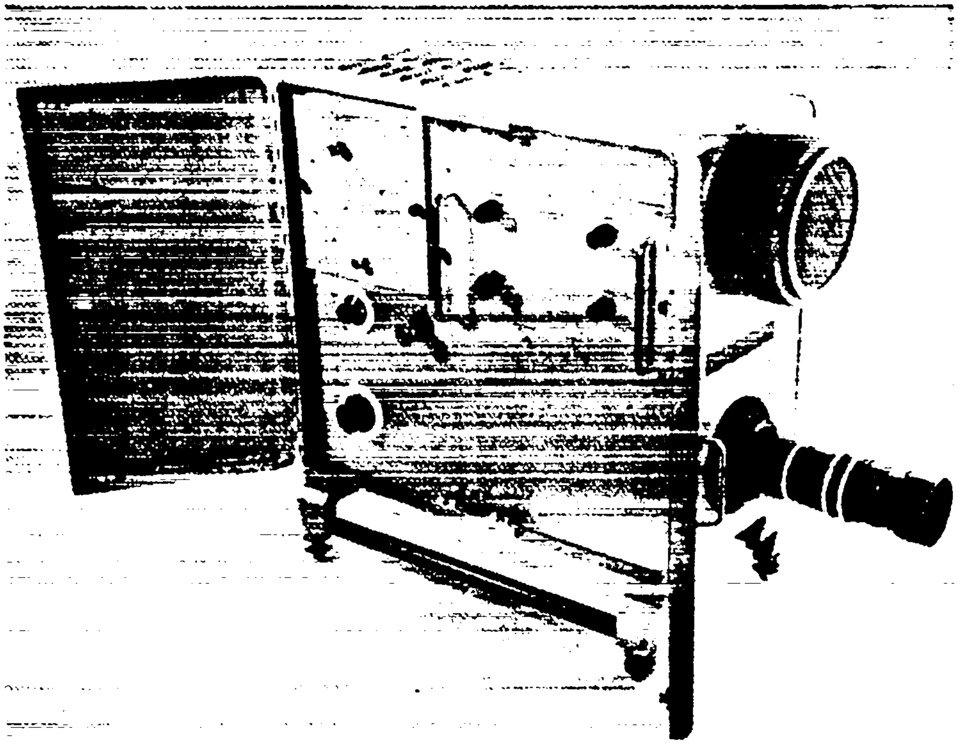

Fig. 5. The E.12 camera.

Four cameras working on this principle have been built, and the perfomances are summarized in Table I. The cameras have been given the type number E.12 and are being made commercially available.*

Camera No. 2 operates at the highest speed at which it is possible to obtain full size images (i.e., at least 15mm square) and at the same time cover the full usable width of the tube screen (about 80 mm). In camera No. 1 a high framing rate of $6 \cdot 10^7$ per second has been provided, with an exposure time of 3nS, by reducing the image size to 6mm square on the screen, and building a special image tube with the photocathode area deliberately restricted to give this size of image. In this way it is possible to obtain higher effective conductivity to the photocathode area, and it is possible with this tube to obtain satisfactory exposures as short as 2nS.

Camera No. 4, which is intended for projectile photography, has 3 speeds of operation, switch control being provided.

The general appearance of the E.12 camera is as shown in the photograph Fig. 5. The only difference between cameras No. 2, 3 and 4 lies in the electronic unit at the top right hand part of the control panel. This is a plug-in chassis, so that changes from one speed of operation to another, may be made simply. For camera No. 1, the fastest version, a special body has had to be built, and this is not readily interchangeable.

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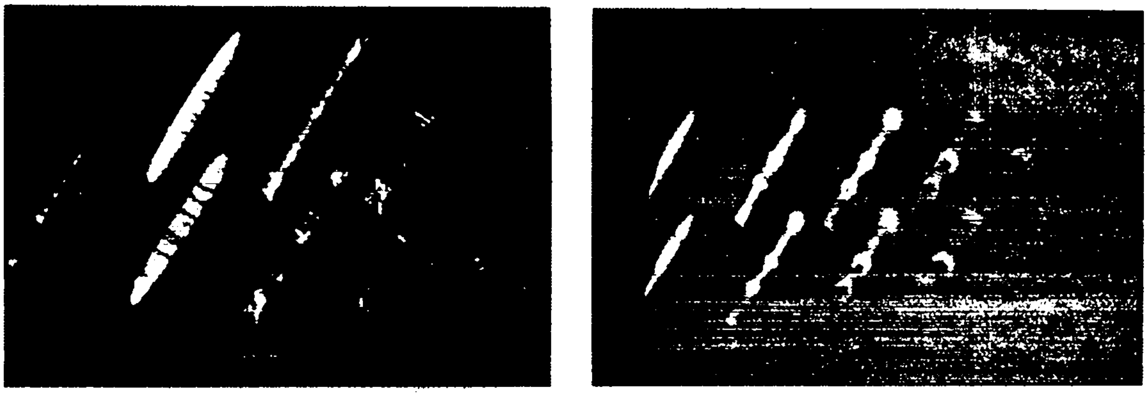
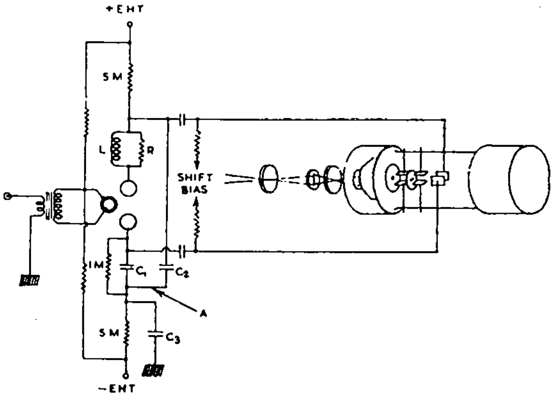
*From John Hadland (P.I.) Ltd., and Telford Products Ltd.



(a) (b)

Fig. 6. Exploding copper wire. 10nS Exposures at 2.10^7 frames per second.



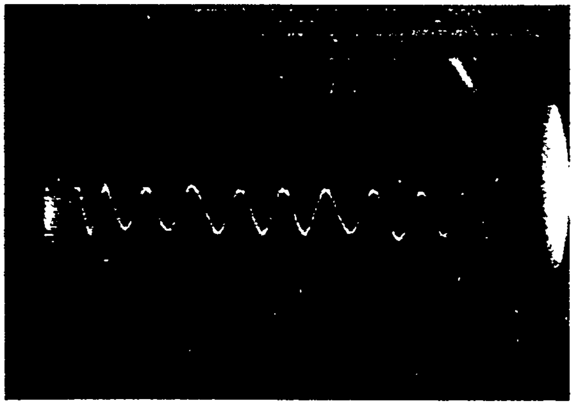


Fig. 7. Scheme of streak camera.

Fig. 8. Streak record, 35nS duration.

Typical E.12 Camera Records

Fig. 6 (a) is a photograph showing the early stages of the explosion of a copper wire ·025mm in diameter, taken with camera No. 2 i.e., the exposure duration per frame is 10nS and the interval between frames is 50nS. Frame No. 1 is at the top left-hand corner and is blank, since the camera started to record before the wire became luminous. Frame No. 2 is immediately below No. 1. No. 3 and No. 4 are, respectively the upper and lower images to the right of Nos. 1 and 2, the sequence then continuing in like manner. Note that by arranging for the exploding wire to be slightly out of the vertical, it is possible to make more efficient use of the screen space available.

In order to determine something of the structure of the bright bands present in Fig. 6(a), the experiment was repeated with the wire mounted obliquely, as shown in Fig. 6(b). The synchronization of the camera was also adjusted to a slightly later time in the phenomenon. Resolution is of course, adversely affected, due to optical reasons, and the ends of the wire are quite out of focus, but in one of the bright bands an interesting "bracelet" effect can be observed.

A STREAK CAMERA

Image tubes fitted with deflector plate systems may be used very effectively in streak cameras, and an efficient and simple system is shown in Fig. 7. The type FE9A image tube is used. Push-pull triangular waveforms are generated in a circuit using a spark gap switch and provide the means of triggered linear deflection of the electron beam. Capacitors C1 and C2 are of equal capacity. C1 is initially discharged, and C2 is fully charged. On receipt of a trigger pulse, the spark gap fires and discharges C2 into C1, accurate symmetry being maintained by keeping the point A at a constant potential by means of capacitor C3. L and R form a linearizing network. The optical arrangements are conventional, consisting of an objective lens, primary slit plane, and relay lens to the tube photocathode. A pair of Canon 50mm $f/1 \cdot 2$ lenses, mounted face to face, is used for the relay lens, and the Dallmeyer Octac 80mm $f/1 \cdot 5$ lens is used, as in the E.12 camera, to relay the screen image to the film. As in the E.12, the overall effective aperture of the camera is that of the objective lens used.

It is possible to obtain very high writing speeds with this camera. The scan time, across the tube face, can be as low as 20nS representing a writing speed of about 4,000mm/μsec. Fig. 8 is a streak record of 35nS duration. The illumination was a fine spot of light from a spark, and a 250 mc/s calibration deflection was applied to one of the pairs of deflector plates in the plane perpendicular to the sweeping deflection. This is an example of a writing speed of 2,500 mm/μS.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the work of Messrs. D. A. Procter, J. M. Stokes, and E. D. Menzies in the development of the various camera systems. Messrs. J. Balderston and S. D. Fussey have been responsible for the A.W.R.E. image tube developments and Mullard Ltd, 20th Century Electronics Ltd, and Mr. R. A. Chippendale, have made major contributions to the image tubes described. Messrs. R. F. Bennett, P. R. Allmark, and G. T. Risley have been responsible for much of the electronic circuit development.

The author also much appreciates the support and encouragement of Mr. I. Maddock and Mr. K. R. Coleman, and thank the Director of the Atomic Weapons Research Establishment for permission to publish this paper.

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(5) Huston, A. E. British Patent Application No. 23211/63.
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APPENDIX B-2

A. E. Huston, "A Multi-Frame Image Tube Camera," reprinted from Kurzzeitphotographie (Proceedings of the Seventh International Congress on High Speed Photography), pp. 93-96, Verlag O. Helwich, Darmstadt, 1967, by permission of the publisher; describes AWRE work on the E 12 cameras.

B–4

A MULTI-FRAME IMAGE TUBE CAMERA

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Introduction

The high-speed framing camera is now a well established tool for many scientific investigations. A very wide range of framing speeds is covered by various optical-mechanical design viz. intermittent-motion film, continuous-motion film with optical compensation, stationary film with rotating mirror, and the great majority of framing camera applications can be successfully handled by these varieties of equipment. There are, however, some fields where mechanical-optical framing cameras exhibit serious shortcomings. These are:

1. Framing speeds above 10^7 per second, where aperture and resolution of rotating mirror cameras have to be sacrificed to an unacceptable degree in order to obtain time resolution.
2. Framing speeds in the region of 10^5 per second which are unattainable by continuous-motion film cameras, and for which an efficient rotating-mirror camera would be unduly large and expensive.
3. Low-light-level applications, where very high aperture is essential.
4. Applications where a triggered camera rather than a continuously-running one is required e. g. in projectile photography.

An image tube framing camera known as the E. 12 has been designed which meets most of these special requirements.

Principle of the New Camera

An image tube may be used as a framing camera in the following way:

1. An image of the phenomenon under investigation is formed on the photo-cathode of the tube by a suitable optical system.
2. The electron beam within the tube is switched on and off repetitively at the appropriate times to give the required shutter action.
3. The electron beam is deflected, suitably synchronised to the shutter action, to a sequence of stationary positions on the screen of the tube.
4. The pattern of images thus produced on the screen is recorded by a stationary camera.

In 1962, at the 6th Congress, an image tube was described [1] which was being developed by A. E. I. (Woolwich) Ltd., under A. W. R. E. sponsorship. A new method of operating this type of tube has been devised [2] which enables the functions 2 and 3 above to be carried out over a wide range of operating speeds without introducing the distortions and severe losses of resolution so common with image tube cameras.

The principle of the camera is shown in Fig. 1. An image of the event under investigation is formed by the objective lens on the photo-cathode of the image tube. The oxidised antimony-caesium photo-cathode is 15 mms. in diameter and is deposited on a conduct-

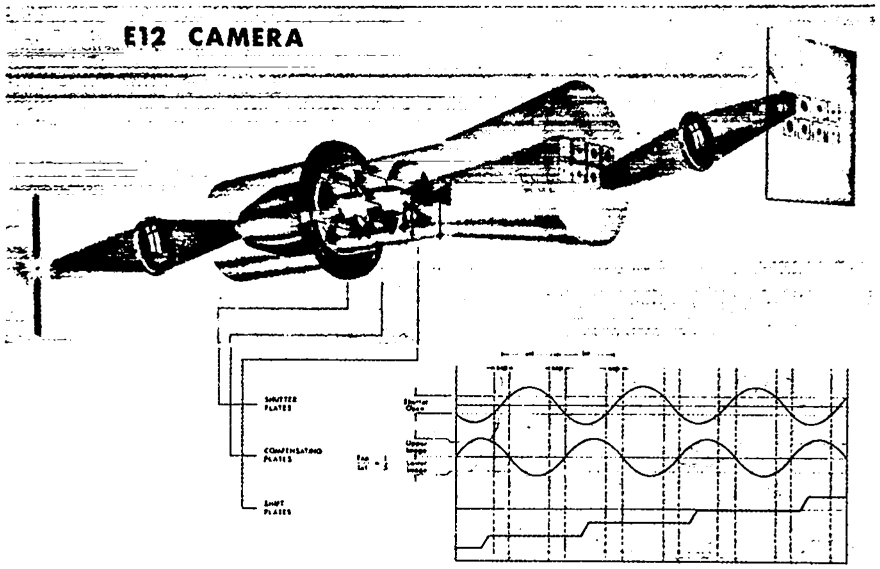

Fig. 1 – Principle of operation of camera.

ing transparent tin oxide layer. The electron beam is accelerated and focused to the fluorescent screen with a linear magnification of 2 times. In the electron drift space between anode and screen are fitted three pairs of deflector plates and the complete action of switching and deflecting the beam is carried out therewith.

The switching action is obtained by deflecting the electron beam across a fixed aperture, using the first pair of deflector plates, the exposure duration being fixed by the time taken to do this. During the open period, of course, the lateral motion of the beam causes the image appearing on the screen to be smeared in the direction of the deflection, and the second pair of deflector plates is used to compensate for this effect by applying to them the same change in potential but in opposite polarity. This method of using the first and second pairs of deflector plates, henceforth designated "shutter" and "compensating" plates respectively, can give an accurately immobilised image on the screen.

To obtain repetitive shuttering, a sinusoidal oscillation is applied to the shutter plates, exposures being obtained when the sinusoid passes through its zero point, i. e. there are two exposures per cycle. A second sinusoid, of the same frequency and amplitude but of differing phase, is applied to the compensating plates. The phase difference is such that alternate exposures are immobilised by different parts of the compensating plates waveform, and appear on the screen of the tube, alternately one above the other. The immobilisation of the images is not quite perfect, since the shapes of the sections of waveform used for compensation, are not exact replicas of the shutter waveforms, but it is found to be sufficiently accurate provided the exposure duration does not exceed one-fifth of the interval between frames.

The third pair of deflector plates, designated the "shift" plates, deflects the beam in the plane at right angles to the shutter and compensating plates. A staircase waveform is applied, synchronised so that the "steps" of the staircase occur between exposures, and the "plateaus" are of sufficient duration to allow two exposures to be completed before the next step. A shift bias maintains sufficient deflection to keep the electron beam just off the edge of the tube screen, until a trigger pulse from the event arrives, when the staircase generator starts to operate.

The Electronic Circuits

The circuits necessary for generating the two phased sinusoids and staircase waveform are extremely simple, and are shown in skeleton form in Fig. 2. An oscillator valve V1 generates a pushpull output of about 1200 volts R. M. S. amplitude, at a frequency corresponding to one-half of the number of frames per second required. This output feeds the shutter plates directly. Another resonant circuit, coupled to the oscillator tank circuit, supplies the phased output required for the compensating plates. The correct phase is obtained by adjustment of tuning and coupling and is remarkably stable in operation. A further coupling coil feeds a signal at the oscillator frequency, in series with a positivegoing triangular waveform, to the grid of the

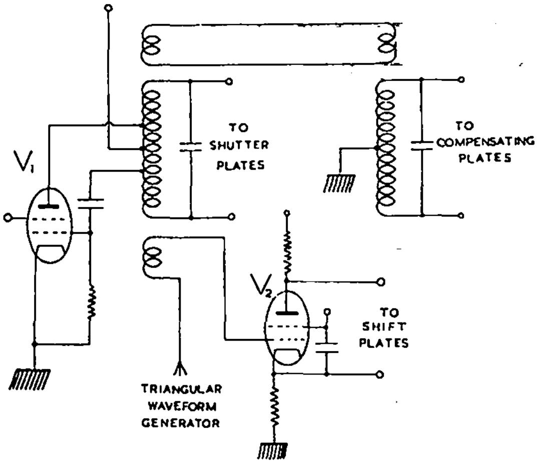

Fig. 2 – Electronic circuits of camera.

integrator valve V2, which is normally biased to cut-off. V2 has equivalent anode and cathode loads and delivers a push-pull staircase waveform to the shift plates. The sequence of images is initiated by triggering the triangular waveform generator, the positive-going output of which overcomes the cut-off bias on V2.

When the sequence of images is completed, the E. H. T. supply to the image tube (20,000 volts) is rapidly removed by triggering a spark gap switch effectively short-circuits the high voltage line. This ensures that, if the event under investigation is still highly luminous after the sequence of images has been completed, there will be no further excitation of the image tube phosphor.

The Camera Performance

Four cameras have been built, all working on this principle, but with different frame rates, numbers of frames, etc. The performances are summarised in Table I.

TABLE I

No.	Frames/ sec.	Exposure Time	No. of Images	Size of Images (mms)	Resolution lp/frame
1	6.10^7	3 nS	6	6 × 6	30 × 30
			12	6 × 3	30 × 15
2	2.10^7	10 nS	8	15 × 15	60 × 60
			16	15 × $7^1/_2$	60 × 30
3	10^6	0.2 μs	10	14 × 14	200 × 200
4	10^5	1 μs	8	16 × 16	200 × 200
			16	16 × 8	200 × 100
			24	16 × 6	200 × 80

Camera No. 2 operates at the highest speed at which it is possible to obtain full size images (i. e. at least 15 mms. square), and at the same time cover the full usable width of the tube screen (about 75 mms.). The limitation lies in the inability of the tube photo-cathode to supply, in less than 10 nanoseconds, sufficient electrons to give a fully recordable image, without local variations in the photo-cathode surface potential appearing. Such variations give rise to distortions in the electron optics of the tube, with attendant distortions of the images on the screen. This problem is, of course, of negligible proportions in cameras Nos. 3 and 4, with their relatively long exposure time per frame.

In camera No. 1, an exposure time of 3 ns, at a framing rate of 6.10^7 per sec., has been provided, in spite of this limitation, by reducing the image size to 6 mms. square, and building a special image tube in which the active area of photo-cathode is only 4 mms. square. Thus higher effective conductivity to the photo-cathode surface is obtained.

A Typical Record

Fig. 3 is a photograph showing the early stages of the explosion of a copper wire 0.25 mms. in diameter, taken with camera No. 2, i. e. the exposure duration per frame is 10 ns and the interval between frames is 50 ns. Frame No. 1 is at the top left hand corner and is blank, since the camera started to record before the wire became luminous. Frame No. 2 is immediately below No. 1. No. 3 and No. 4 are respectively, the upper and lower images to the right of Nos. 1 and 2, and the sequence continues in the same manner. Note that by arranging for the exploding wire to be slightl out of the vertical, it is possible to make more efficien use of the screen space available.

Fig. 3 – Exploding copper wire 10 ns exposures at 2.10^7 frames per second.

Acknowledgements

The author wishes to acknowledge the work of Mr. D. A. PROCTER and Mr. P. R. ALLMARK in the development of the camera, and of Mr. R. A. CHIPPENDALE in the development of the image tube. The author also much appreciates the constant support and encouragement of Mr. I. MADDOCK and Mr. K. R. COLEMAN, and thanks the Director of the Atomic Weapons Research Establishment for permission to publish the paper.

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[2] HUSTON, A. E.: "High-speed Image Tube Camera using sinusoidal waveforms". British Patent No. 23211/63.

Summary

A new image tube camera has been developed in which the interruption of the electron beam, which controls shutter action, is achieved by deflection of the beam, in a sinusoidal manner, over an aperture in the tube. Another sinusoidal deflection, in the same plane, permits two immobilised images to be obtained on the screen. A third deflection, of staircase form, triggered from the event under investigation, enables a sequence of images to be recorded.

Four cameras of this design have been built.

Résumé

On a développé une nouvelle caméra à transformateur d'image où l'interruption du faisceau électronique, qui assure l'obturation, est réalisée par déflexion du faisceau, de manière sinusoïdale, sur une ouverture dans le tube. Une autre déflexion sinusoïdale, dans le même plan, permet d'immobiliser deux images sur l'écran. Une troisième déflexion, en forme d'escalier, synchronisée avec le phénomène étudié, permet d'enregistrer une série d'images.

Quatre caméras de ce type ont été construites.

Zusammenfassung

Eine neue Bildwandlerkamera wurde entwickelt, bei der die Unterbrechung des Elektronenstrahls und damit die Steuerung des Verschlusses durch sinusförmige Ablenkung über eine Blendenöffnung in der Röhre hin erzielt wird. Durch eine weitere sinusförmige Ablenkung in derselben Ebene ergeben sich zwei ruhende Bilder auf dem Schirm. Eine dritte, stufenförmige Ablenkung, die durch das zu untersuchende Ereignis ausgelöst wird, macht es möglich, eine Folge von Bildern aufzuzeichnen.

Vier Kameras dieser Art wurden gebaut.

APPENDIX B-3

A. E. Huston, "Streak and Multi-Channel Photography Using Image Tubes," reprinted from Kurzzeitphotographie, pp. 97-101, by permission of the publisher; describes AWRE work on E 14 cameras.

B–5

STREAK AND MULTI-CHANNEL PHOTOGRAPHY USING IMAGE TUBES

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Introduction

A number of workers have published, in recent years, details of equipments which exploit the possibilities of the single-stage image tube as an active component in a high-speed camera. Image tubes have considerable versatility, in that the electron beam may be: –

1. Switched on and off rapidly to act as a shutter giving a single exposure.
2. Deflected continuously across the screen to form a streak camera.
3. Switched repetitively, and deflected in discrete steps, forming a ciné camera.

A recent development in category 3 is described by the author in another paper presented at this Congress [1], and it is the purpose of the present paper to outline some developments in the application of electrostatically focused tubes in cameras of types 1 and 2.

The Image Tube as a Shutter

The requirement is simply that the electron beam in the tube be allowed to proceed from photo-cathode to screen only for the duration of the exposure desired. Some tubes designed for shutter operation include special electrodes intended to act as gating points, in fact making the tube into a triode. With such tubes it is possible to gate the electron beam with a pulse of amplitude, say, 250 volts, but there is a considerable disadvantage in that a pulse of almost ideal shape is essential (i. e. the rise and fall times of the pulse must be very small compared with the total duration, and the top of the pulse must be flat to a high degree of accuracy). This necessity arises because, for a given anode voltage, the tube is in correct focus for one value only of the gating electrode voltage.

A more direct method of pulsing is to apply the whole tube potential in the form of a pulse. The tube in this case operates as a diode. The disadvantage of course is that it is necessary to generate a pulse of some 15–20 Kv., but, on the other hand, pulse shape is unimportant, since diode tubes may be designed to maintain their focus over a wide range of applied voltage [2]. This method of operation is found to be preferable when exposures in the 100 nS region or less are required.

It is extremely important, in focused image tubes, that the photo-cathode is of high electrical conductivity. In order to obtain sufficient light output from the tube to give a recordable image on the film, it is necessary to bombard the screen with a sufficient number of electrons, this number being substantially constant regardless of exposure time. The shorter the exposure, however, the greater is the current associated with this number of electrons, and for exposures in the region of 10 nanoseconds might be as high as 100 milliamps. If the conductivity of the photo-cathode is inadequate, a current of this magnitude causes local variations of cathode surface potential which leads to distortion of the electron optics of the tube, in turn leading to poor resolution and geometrical distortion of the image on the screen. Experience has shown that resistivities at least as low as 100 ohms per square are highly desirable, and transparent conducting substrates to the photo-cathodes must be provided.

The Single-frame Camera

Fig. 1 shows the scheme of a single-frame camera using a diode image tube. The technique for generating the high-voltage pulse is very simple, consisting of a co-axial cable and a triggered spark gap. The pulse is of amplitude equal to the E. H. T. supply line, and its duration is determined by the cable length. The resistor R matches the characteristic impedance of the cable. The switch is a corona-triggered spark gap [3] and has proved to be very reliable in practice. A trigger pulse of 200 volts, of either polarity, is sufficient to trigger the switch with the 5/1 step-up pulse transformer shown. The triggering delay is 65 nS, with a jitter of ± 2 nS.

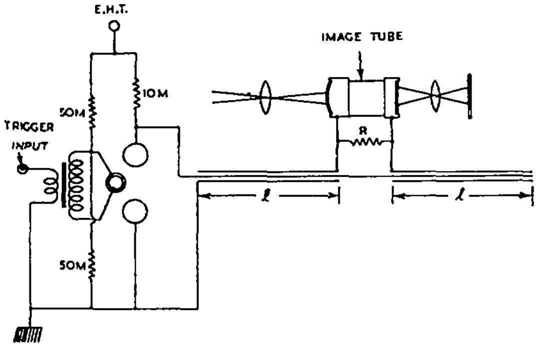


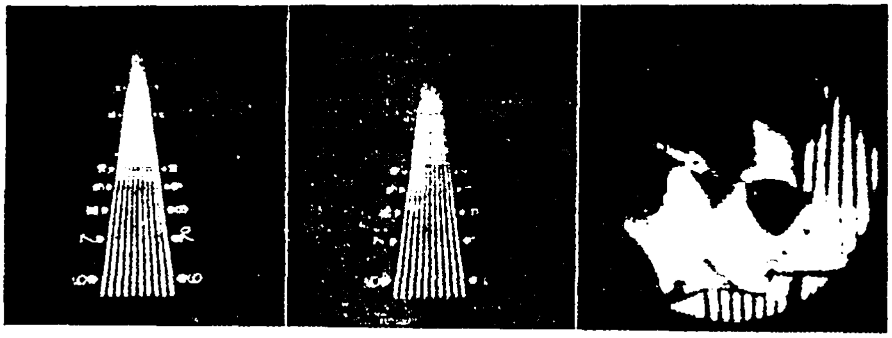
Fig. 1 – Scheme of single-frame camera.

A number of cameras of this type have been built using the 6929 image tube. This tube has a spherical photo-cathode surface and a plane screen. Towards the edge of the field the resolution deteriorates seriously, and a considerable degree of pin-cushion distortion is evident. These effects are aggravated if a standard photographic lens is used for the objective. The simplest solution is to restrict the area of photo-cathode actually used to about 10 mms diameter. Under these circumstances, there is very little pin-cushion distortion, and loss of resolution at the edge of the field is slight. It is also possible to employ standard objective lenses as the spherical image surface can be accommodated over this small area. The resolution per frame width, under pulse conditions, is of the order of 250 line pairs. Fig. 2 shows records of resolution charts (a) the static resolution, about 35 line pairs/mm (b) the resolution when pulsed for 30 nS duration, about 22 line pairs/mm (c) an image, obtained with ruby laser illumination, at 30 nS exposure time.

The 6929 tube is normally manufactured with an S. 1 photo-cathode, and this was in fact the type used to obtain record 2(c), as the S. 1 cathode has good sensitivity at the ruby laser wavelength. The camera has been used by CHRISTIE [4] in his photographic radar experiments with lasers. For other purposes the S. 11 photo-cathode is more useful, and *Mullard Ltd.* have supplied samples of the 6929 tube with S. 11 photo-cathodes deposited on highly conducting transparent substrates.

Multi-channel Cameras

A series of single-frame cameras, as described above, may be operated in sequence to give, in effect, a ciné camera. The advantage of this technique over the multiple-frame camera described in ref. [1] is that each exposure, and the interval between exposures, may be independently adjusted. A disadvantage is that



a b c

Fig. 2 – Records taken with single-frame camera.

the separate channels have different lines of sight to the event being photographed, though this may be overcome, if necessary, by the use of a beamsplitting system at the objective.

The multi-channel camera is particularly advantageous if images of high resolution are required, as each channel may be designed efficiently without, for example, the loss of resolution due to deflection of the electron beam which occurs in the multiple-frame type of image tube camera. An advanced multi-channel design is the A. W. R. E. 6 E. 14 camera which is at present under development. The image tube, type F. E. 11 has been specially designed to give 1250 line pairs per frame width, and this has necessitated spherical cathode and screen surfaces. This in turn has necessitated special optical systems to match these curvatures, and their design is discussed in the paper by REID [5] presented at this Congress. The F. E. 11 tube operates at 20 KV, and uses a development of the circuit arrangement shown in Fig. 1. The exposure duration may be varied in steps from 50 nS to 300 nS, but is normally used at 150 nS. Initial samples of the F. E. 11 tube have an S. 11 photo-cathode, with a tin oxide transparent conducting substrate, and the next stage of development is to incorporate a cathode window material having transmission down to 3000 Å. Finally an S. 20 photo-cathode, having a metallic conducting substrate, is to be used, to extend the spectral range to 7500 Å.

The 6 E. 14 camera has six complete channels, each with its own objective, image tube, pulse circuitry, relay optics, and film holder, and a separate programming unit supplies adjustable trigger pulses to enable the individual channels to be triggered as required.

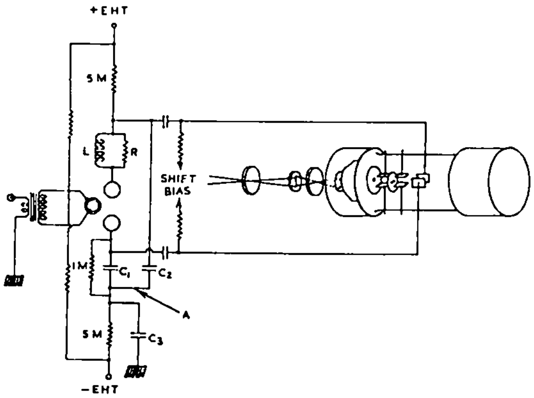


Fig. 3 – Scheme of streak camera.

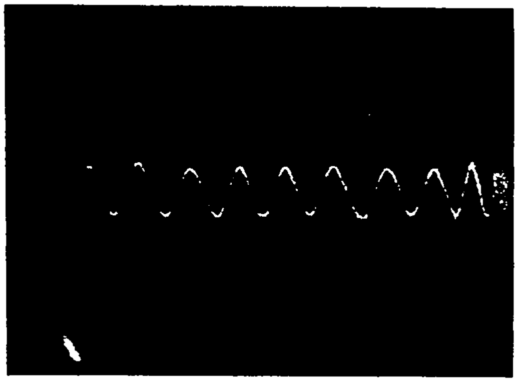


Fig. 4 – Calibration wave (250 mc/s.).

Streak Photography

Image tubes fitted with deflector plate systems may be used very effectively in streak cameras, and an efficient and simple system is shown in Fig. 3. The image tube, Type F. E. 9A ist fitted with three sets of deflector plates and may also be used in the multiple-frame camera (Ref. [1]). The push-pull triangular waveforms required for linear deflection of the beam are generated in a circuit which is a combination of the spark gap switch [3], and a capacitor network, as used by DEMIDOV et al [6] in an image-tube streak camera. Capacitors C 1 and C 2 are of equal capacity. C 1 is initially discharged, and C 2 is fully charged. On receipt of a trigger pulse, the spark gap fires and discharges C 2 into C 1, accurate symmetry being maintained by keeping the point A at constant potential by means of the capacitor C 3. L and R form a linearizing network. The optical arrangements are conventional, consisting of an objective lens, primary slit plane, and relay lens to the tube photo-cathode. A Dallmeyer Octac 80 mm f/1.5 lens is used to relay the screen image to the film plane. This lens operates at unity magnification so that the effective aperture at this point is f/3.

Fig. 4 is a streak record of 35 nS duration. The illumination was a fine spot of light from a spark source, and a 250 mc/s calibration deflection was applied to a pair of deflector plates in the plane perpendicular to the sweeping deflection. This represents a writing speed of 1200 mm/µs, and there has been no difficulty in obtaining speeds up to about 2500 mm/µs with the system.

Ultra-violet Image Tube Camera

A special version of the F. E. 9A image tube, known as the F. E. 14, has been developed for use as a streak or framing camera in the wavelength range 1800 Å to

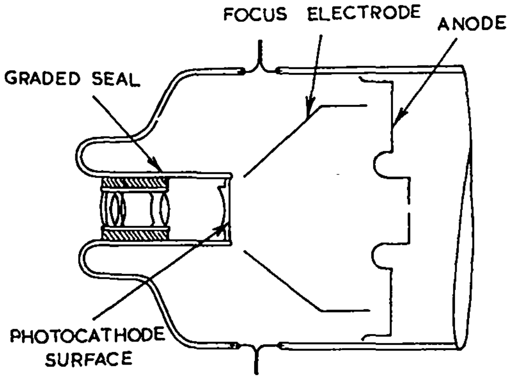


Fig. 5 – Assembly of cathode end, and objective lens, of FE. 14 ultra-violet image tube.

3000 Å, and the relevant parts of the tube structure are shown in Fig. 5. Electron-optically, the tube is identical with the F. E. 9A as depicted in Fig. 3, but, for this wavelength range, it is essential to dispense with the glass end window of the F. E. 9A tube. Accordingly, a silica component is used to carry the photosensitive surface, and is made part of the objective lens as described in the paper by BROWN [7] presented at this Congress. The silica is matched to the glass envelope of the tube by means of a graded seal in the position shown. The photo-cathode is caesium-tellurium, formed on a transparent conducting substrate of nickel. The quantum efficiency is about 5%.

Acknowledgements

The author wishes to acknowledge the work of Mr. E. D. MENZIES, and Mr. J. M. STOKES in the development of the camera systems. Mr. G. T. RISLEY and Mr. R. F. C. BENNETT designed the 20 KV pulse system for the 6 E 14 camera. *Mullard Ltd.* have co-operated in the development of diode image tubes and have manufactured sample tubes with special photo-cathodes.

The interest and encouragement of Mr. I. MADDOCK and Mr. K. R. COLEMAN is much appreciated. The author also thanks the Director of the Atomic Weapons Research Establishment for permission to publish the paper.

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Summary

The single-stage, electrostatically-focussed image tube may be successfully employed as a short-duration shutter provided the photocathode is capable of supplying adequate current density. Such a device has been developed into a single-frame camera of high resolution by designing the image tube with spherical cathode and screen surfaces and evolving special systems which match these curvatures. The electronic circuitry is simple. Six of these units have been mounted together in one assembly, forming a multi-channel camera. The exposure time is normally set at 150 nS, and the resolution per frame width is 1250 line-pairs.

A fast streak camera has been designed, based on the FE9A image tube, giving, with a simple electronic circuit, writing speeds greater than 1500 mm/μS. A special ultra-violet version of the tube carries a caesium-tellurium photocathode and an integral optical system.

Résumé

Le transformateur d'image à focalisation électrostatique, à un seul étage, peut être utilisé avec succès comme obturateur de courte durée, pourvu que la photocathode puisse fournir une densité de courant suffisante.

On a développé un tel dispositif en caméra de haute résolution à image unique en calculant le tube à image avec des surfaces de cathode et d'écran sphérique et en concevant des systèmes optiques spéciaux qui compensent ces courbures. Le circuit électronique est simple.

On a assemblé six de ces unités pour obtenir une caméra à cannaux multiples. Le temps d'exposition est normalement fixé à 150 ns et la résolution par largeur d'image est 1250 paires de lignes.

On a calculé une caméra à fente, à partir du tube à image F. E. 9A, qui donne, avec un circuit électronique simple, des vitesses de balayage plus grandes que 1500 mm/µs. Une version spéciale du tube pour l'ultraviolet porte une photocathode césium-tellure et un système optique intégré.

Zusammenfassung

Die einstufige, elektrostatisch fokussierte Bildröhre kann erfolgreich als Kurzzeitverschluß verwendet werden, falls die Photokathode eine genügend hohe Stromdichte zu liefern vermag. Eine solche Anordnung wurde zu einer Einzelbildkamera hohen Auflösungsvermögens entwickelt, indem die Bildröhre sphärische Kathoden- und Leuchtschirmoberflächen erhielt und spezielle, an deren Krümmung angepaßte optische Systeme entwickelt wurden. Die elektronische Schaltung ist einfach. Sechs dieser Einheiten wurden in einer Anordnung zusammengefaßt und bilden so eine Vielkanalkamera. Die Belichtungszeit ist gewöhnlich auf 150 nsec eingestellt, und die Auflösung je Bild beträgt 1250 Linienpaare.

Auf der Grundlage der Bildröhre FE 9A wurde eine schnelle Streakkamera entwickelt, die mit einer einfachen elektronischen Anordnung Schreibgeschwindigkeiten von mehr als 1500 mm/µsec erreicht. Eine besondere Ultraviolett-Ausführung dieser Röhre ist mit einer CS-Te-Photokathode und fest eingefügtem optischem System versehen.

APPENDIX B-4

C. D. Reid, "Optics For Use With High Definition Image Converter Tubes Having Curved End Windows," reprinted from Kurzzeitphotographie, pp. 431-436, by permission of the publisher; describes AWRE work on the optical design of the E 14 cameras.

SEKTION H:

HILFSGERÄTE
AUXILIARY EQUIPMENT
APPAREILS AUXILIAIRES

H-1

OPTICS FOR USE WITH HIGH DEFINITION IMAGE CONVERTER TUBES HAVING CURVED END WINDOWS

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Some high-definition image converter tubes recently developed have strongly-curved cathode and phosphor end windows. The shapes of the tube ends are dictated by electron-optical requirements; the windows are spherical and nearly concentric, so that they are convex outwards. Fig. 1 shows a typical design of tube: its end windows are 44 mm radius of curvature for the cathode and 39 mm radius for the phosphor.

Tube ends of these shapes present interesting problems in the design of suitable camera objective and copying systems. Fig. 2 shows the required optical layout. Conventional objectives are apt to produce field curvatures of the opposite sense, i. e. concave towards the objective, and this can be corrected only by putting a lens of the necessary negative power close to the cathode. Such an arrangement may well suffer considerable astigmatism. If the objective is required to be achromatic over a considerable wavelength range the difficulties may be too great for conventional designs to be applicable.

The problems of matching optics to the cathode and phosphor ends of the image tube possess some similar

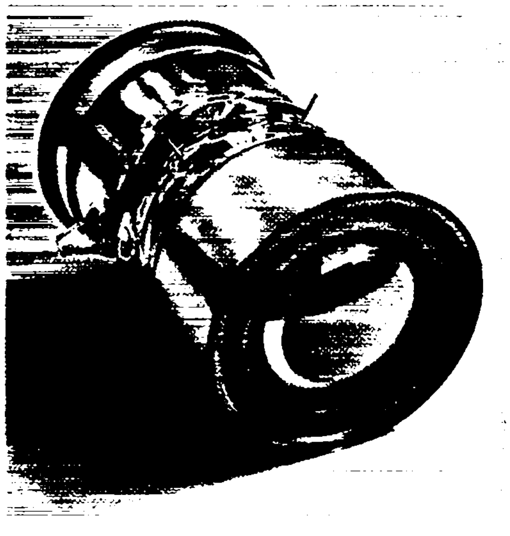

Fig. 1 – High Definition Image Converter Tube.

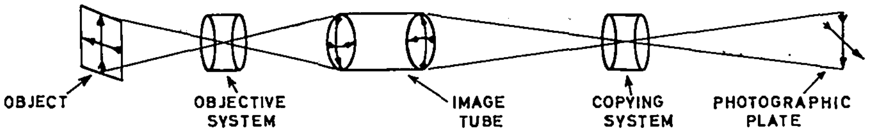

Fig. 2 – Scheme of Optics Needed to Work with High Definition Tube.

features, but do not necessarily lead to the same solutions. This may best be illustrated by stating the specifications laid down for the camera type 6E.14 described by HUSTON [1] in another paper given at this Conference. These specifications are:

(a) *Camera objective.* To cover a field 3° in diameter, to work within the wavelength range 3,000 to 9,000 Å, to present its final image on a cathode 4.0 cm diameter and 4.4 cm radius of curvature, and to yield at least 1200 picture line pairs over that diameter, finally to work at a relative aperture of f/20.

(b) *Copying system.* To transfer the image from a phosphor screen 4.0 cm diameter and 3.9 cm radius of curvature on to a flat film, the relative aperture of the system to be not less than f/2. The wavelength range required is restricted by the phosphor response (Fig. 3).

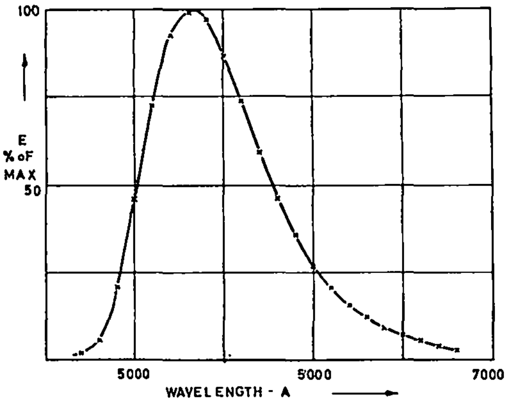

Fig. 3 – Spectral Characteristics of Phosphor.

The Camera Objective

After some preliminary studies had shown that conventional optical systems could not be made to meet the specification, several alternative designs were investigated, and one variation made.

The basic design argument for the objective is simple. Concave mirrors produce image fields which are curved in the right sense, therefore the imaging should be achieved by what is essentially a reflecting system. However, an image field 3° in extent and 4.0 cm actual diameter implies an equivalent focal length of about 80 cm, hence to obtain both this focal length and the image field curvature two concaves will be necessary.

The preliminary form for the design is therefore that of a Gregoryan telescope, except that the simple design is not itself sufficiently well corrected to give an adequate performance over the whole field. At fields up to about 0.7° diameter a straight-forward Gregoryan, i. e. paraboloid primary and ellipsoid secondary, should be acceptable at these apertures, but the larger field requires an improved arrangement.

If both the primary and secondary mirrors in the Gregoryan arrangement are replaced by appropriate Schmidt camera units, the difficulties of obtaining adequate resolution, field coverage and field curvature disappear. The primary and secondary sections of the objective can be made quite highly corrected, the major outstanding monochromatic aberration being astigmatism which for $1^{1}/_{2}$° semi-field is too small to be troublesome.

Fig. 4 shows the first double-Schmidt concept, using refracting corrector plates. The Schmidt sections face each other and are co-axial: to allow light to pass each unit is in fact an off-axis part of a complete camera. Were it not for the extreme range in wavelengths, this form of objective should perform moderately well. However, there appears to be no easy way of achromatising a corrector plate sufficiently well to achieve an adequate performance between 3,000 and 9,000 Å. The best that seemed possible did not appear likely to give more than about 7 line pairs per mm at the extremes of the wavelength range. Not the least of the difficulties lay in finding an adequate flint-type medium transparent at 3,000 Å.

Complete achromatism is achieved by using reflecting instead of refracting corrector plates, as shown in Fig. 5. These plates have to be tilted with respect to the common axis of the two Schmidt camera sections, but each may be designed independently of the other. A version of this design has been made and is shown in Fig. 6. The primary plate is tilted at 7° to the axis, whilst the secondary is tilted at 10.25°. These angles were chosen to bring the entering and imaging beams

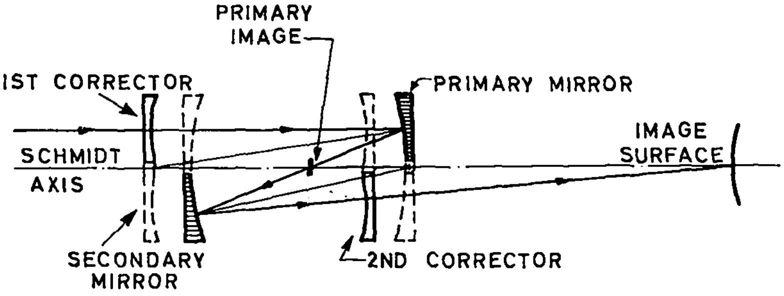

Fig. 4 – Arrangement of Double Schmidt Objective with Refracting Corrector Plates.

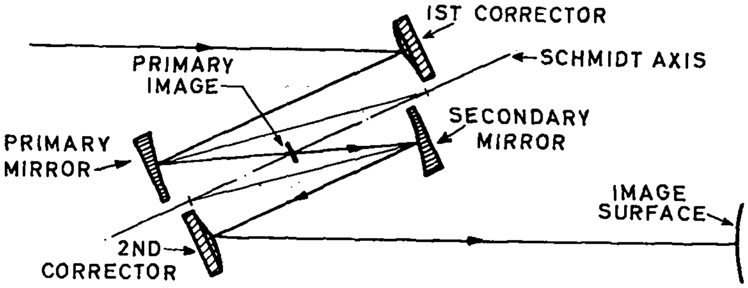

Fig. 5 – Arrangement of Double Schmidt Objective with Reflecting Corrector Plates.

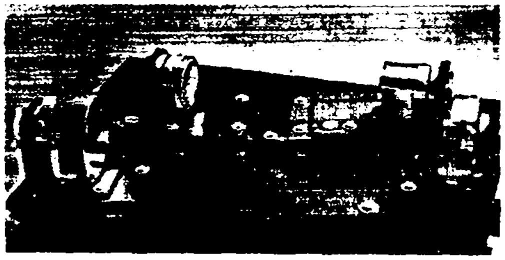

Fig. 6
The Double Schmidt Reflecting Objective.

of light as close as possible to parallel with the axis without being intercepted by the concave mirrors.

The main difficulty with this form of objective lies in the manufacture of the corrector plates. However, these may be made initially as surfaces of revolution, with some local retouching to remove the astigmatism caused by tilting. For the particular design made, four of the first section corrector plates may be obtained from the starting blank, and three of the second section, hence the problems of making a series of objectives are reduced somewhat in severity.

Fig. 7 shows the image quality achieved with the first objective made to this design.

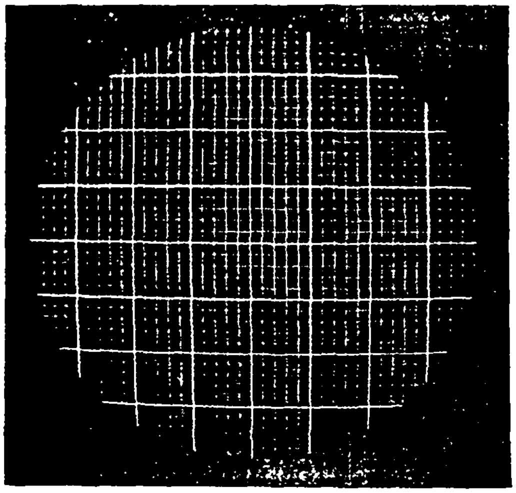

Fig. 7 – Test Chart Photographed with Double Schmidt Reflecting Objective.

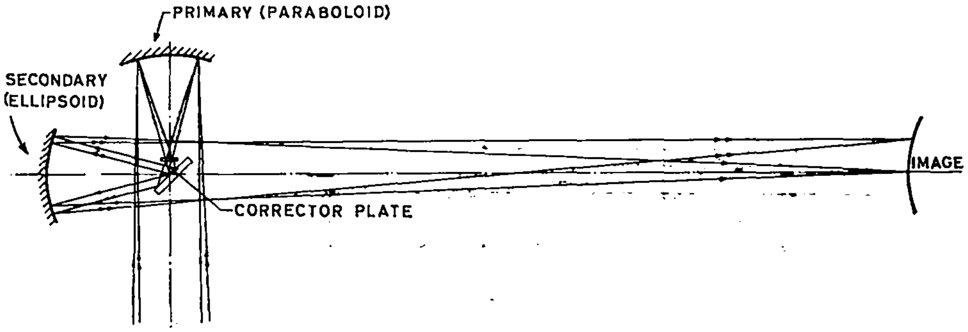

Fig. 8 – Layout of Cruciform Objective.

Several other varieties of reflecting objective have been proposed. The general form may be modified as suggested by C. G. Wynne [2] by setting a small Newtonian flat mirror at 45° to the axis of the primary system. The resulting layout is thus cruciform (Fig. 8), and in Dr. Wynne's proposal consists of a folded Gregoryan with an aspheric corrector plate set near the primary image. In direct form, with the smallest components for a given aperture, this scheme does not produce such a compact camera as the double Schmidt, but, of course, it may be folded. Alternatively, the relative proportions of the optics may be changed.

A cruciform double Schmidt is also feasible; if designed with correct tilts on the reflecting corrector plates, the plates may be surfaces of revolution with compensation for astigmatism.

It is clear, therefore, that a number of designs of curved field objectives are available for applications with image tubes. The choice depends on the conditions of use, e. g., the degree of achromatisation needed, on the geometrical layout the camera must conform to, and also on the difficulty of manufacture. The best solution for one camera need not be the best for another.

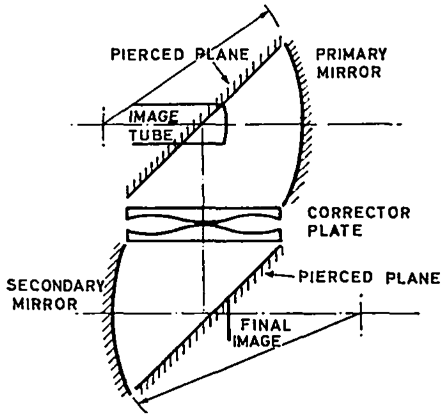

Fig. 9 – Double Schmidt Copying System.

The Copying System

The best solution of the copying problem is to use a fibreoptic faceplate as the phosphor-carrying tube end, the interior surface being curved to suit the electron optics, whilst the outer face is flattened to carry the photographic film. No doubt this will be the method used to fulfil the copying function when tubes with vacuum tight faceplates become readily available. Until then, however, rather less elegant methods are necessary.

Two basic methods are available: one in which the field curvature is reduced to zero by a fibre-optic plate, and the second in which it is reduced optically.

A possible optical method is to use a double Schmidt system, as shown in Fig. 9. A pair of similar Schmidt

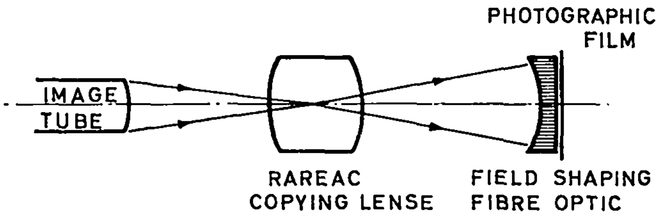

Fig. 10 – Copying System with Fibre Optic Field Flattener.

cameras are arranged face to face, 45° plane mirrors being required to make both the phosphor surface and the final image plane accessible. If the radii of curvature of the Schmidt's focal surfaces are each twice that of the tube end, the final image is plane. This system may be used if the tube end is small enough to keep the obstruction ratio within tolerable limits (say, 30% of area). It cannot be claimed that the overall effect is elegant, however.

In the model built for the 6E.14 camera, the copying was achieved using a Dallmeyer Rareac system, working at f/2, focussing an image of the tube end on to a Sunbury Glasswork's solid fibre-optic field flattener (Fig. 10). The photographic film was pressed up against the flat rear surface of the fibre-optic. This system yielded a resolution of some 80 line pairs per mm, and is thus more than adequate for this application.

Conclusions

Low aperture objectives fundamentally similar to the Gregoryan telescope can be designed to yield the strong negative curvature of image field needed to cover the cathodes of the high-resolution, curved-end image converter tubes. Comparatively high-aperture copying systems may be feasible with a double-Schmidt system, or with commercially available copying lenses used in conjunction with fibre-optic field-flatteners.

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Summary

Recent designs of high-resolution image converter tubes have cathode and phosphor tube ends formed as strongly curved convex menisci. The radii of curvature of these ends are comparable with the diameters of the tube ends.

This field curvature is too strong for conventional optics to match, and the requirements may be made more stringent by the need to cover a considerable range of wavelengths. A recent example is intended to work between 3000 and 9000 Å.

Neither the camera objective nor the copying systems therefore can use conventional systems.

Some interesting new designs have been proposed. Reflecting objective systems can be designed to produce negative field curvature of appropriate strength coupled with considerable freedom in choice of focal length and, of course, complete achromatism. Copying systems can also be built as reflectors, although there may be considerable obstruction by some designs of image tube, or fibre optics can be used to obtain the matching between image curvature and photographic film plane.

Résumé

Les récentes réalisations de tubes convertisseurs d'image à haute résolution possèdent des extrémités cathode et phosphore qui se présentent sous forme de ménisques convexes à forte courbure.

Cette courbure de champ est trop importante pour être compensée avec les systèmes optiques conventionnels et on peut rendre plus sévères les exigences en s'astreignant à couvrir un domaine considérable de longueurs d'onde.

On se propose de travailler sur un exemple entre 3000 et 9000 Å. C'est pourquoi, ni l'objectif de la caméra ni le système de reproduction ne peuvent faire appel aux procédés conventionnels.

On a proposé plusieurs nouvelles réalisations intéressantes. On peut concevoir des systèmes objectifs réfléchissants de façon à produire une courbure de champ négative adaptée quantitativement et doué d'une grande liberté en ce qui concerne la distance focale, et, bien sûr, un achromatisme complet. Les systèmes réproducteurs peuvent aussi se construire en réflecteurs, bien que cela présente des difficultés considérables du fait de certaines conceptions du tube à image; ou encore on a la possibilité d'utiliser des fibres optiques en vue d'obtenir la correction entre la courbure d'image et la planéité du film photographique.

Zusammenfassung

Bei den neu entwickelten Bildwandlerröhren hoher Auflösung sind Kathode und Abbildungsschirm in der Form konvexer Menisken ausgebildet, deren Krümmungsradien den Röhrendurchmessern vergleichbar sind.

Diese Bildfeldwölbung ist zu groß, als daß sie durch übliche optische Systeme ausgeglichen werden könnte. Diese Bedingungen können noch weiter, durch den benötigten weiten spektralen Übertragungsbereich, erschwert werden. Man beabsichtigt neuerdings den Be-

reich zwischen 3000 und 9000 Å in einem Beispiel auszunutzen.

Daher können weder für das Kameraobjektiv noch für die Schirmabbildung übliche Systeme verwendet werden.

Einige interessante neue Methoden haben sich ergeben. Zur Erzielung einer ausreichend starken, negativen Bildfeldwölbung für das Aufnahmeobjektiv können Spiegelsysteme verwendet werden, die einen beträchtlichen Spielraum in der Wahl der Brennweite zulassen und völlig achromatisch sind. Für die Schirmabbildung können ebenfalls Spiegelsysteme verwendet werden, wenn sich dabei auch beträchtliche Einschränkungen wegen einiger Konstruktionseigenschaften der Wandler ergeben. Schließlich kann man die Bildwölbung gegenüber der Filmebene noch durch die Verwendung einer Fiberoptik ausgleichen.

DISCUSSION

W. MÜLLER: Welches ist die wirksame Öffnung der Objektive?

C. D. REID: 1 : 20.

W. MÜLLER: In Deutschland wurden um 1942 bei Zeiss in Jena Objektive für die bei der AEG entwickelten Bildwandlerröhrer gebaut, deren Bildfeldkrümmung der Krümmung der Kathode des Bildwandlers angepaßt war. Die Öffnung dürfte bei 1 : 3 gelegen haben. Das Auflösungsvermögen war besser, als es die damals benutzten Phosphor-Schirme verlangten. Die Objektive waren für den sichtbaren Spektralbereich bestimmt. Eines der Objektive ist im Deutsch-Französischen Institut in St. Louis noch vorhanden. Ich werde versuchen, im ISL nähere Angaben zu erhalten und gegebenenfalls diese Bemerkung ergänzen.

APPENDIX B-5

W. A. Waller, "A Framing Drum Spectrograph," reprinted from Kurzzeitphotographie, pp. 102-104, by permission of the publisher; describes the AWRE work on SPREFS.

B-6

A FRAMING DRUM SPECTROGRAPH

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For the photography and spectroscopic measurement of rapidly moving events and expanding light sources, fast time and high spectral resolution can be achieved simultaneously, by combining a dispersing optical system with a high speed camera. In this manner, a time versus wavelength record, or time-resolved spectrum of the event can be obtained. If however, in addition to time and wavelength, spatial resolution and a continuous access facility are required, that is, non-synchronisation of the event and camera, the problem of satisfying all these parameters simultaneously becomes increasingly difficult.

A continuous access framing spectrograph is described which is capable of photographically recording spectra, at a frequency of 100,000 frames per second, in the wavelength range 3000 to 9000 Å. The instrument uses an F/3 reflecting optical system, with a 600 lines per millimetre plane grating as the dispersing element, giving a dispersion of 50 Å per millimetre. A resolution of 5 Å is obtained over the whole spectral range being recorded.

To achieve spatial resolution, a multi-channelled image transformer, reduces the field of view of the objective lens to a slit at the entrance to the spectrograph.

The Framing Drum Spectrograph consists essentially of an objective lens and a spectroscopic optical system recording frames of spectra on a 15 inch diameter drum rotating at 7,000 r. p. m. in a low pressure. The combined optical system, in conjunction with an image

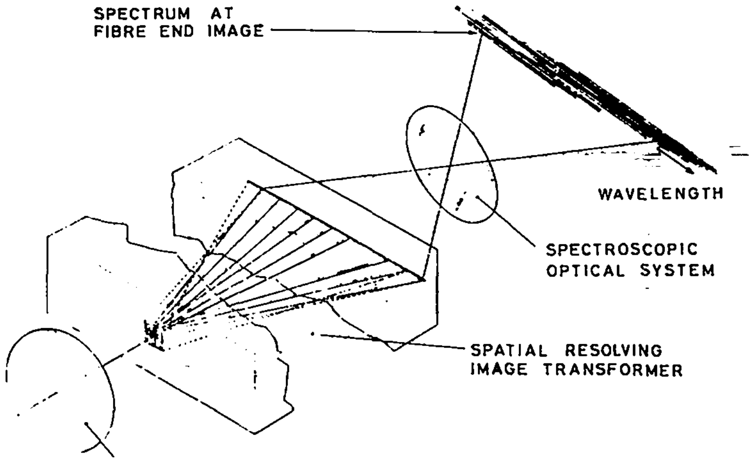

Fig. 1

movement synchronisation system, produces 900 discrete frames of spectra formed from the spatially resolved image of an event under investigation. The frames are recorded on a length of 5 inch wide photographic film, with a frame interval and exposure time of 10 microseconds, and a total recording time of 9 milliseconds. The film is held in a darkroom loaded cassette which is rigidly mounted on the inside diameter of the rotating drum.

An objective lens, of which a range is available, images the requisite field of view of the event on the entrance aperture of an optical image transformer. The transformer is located between the objective lens and the spectroscopic optical system, and consists of one hundred coated quartz fibres, each 200 microns in diameter. The fibres are layered and orientated such that the fibre ends form a 2 millimetre square light receptive area at the entrance end, and a light emitting slit, 20 millimetres long and one fibre diameter in width, at the exit end of the transformer. It has been designed to give maximum displacement along the length of the exit slit of adjacent fibres at the entrance end. Figure 1 shows the arrangement of the image transformer with the square light receptive area and light emitting slit at the ends.

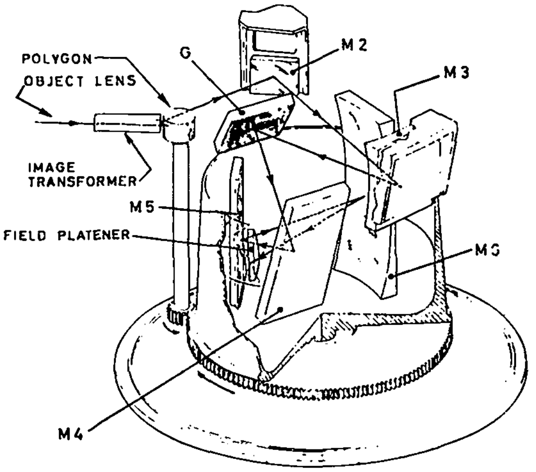

Fig. 2 – Optical system of framing spectrograph

Figure 2 illustrates the optical system of the spectrograph. The multi-channelled slit of the image transformer acts as the entrance slit of the spectroscopic optical system, and is followed by a plane folding mirror (M 2) and an off-axis, parabolic collimating mirror (M 3). A *Bausch & Lomb* plane grating (G) disperses the collimated light from each of the fibre ends forming the slit, and a second spherical concave mirror (M 6), with the grating at its centre of curvature, produces via the plane mirrors (M 4) and (M 5) a spectrum at the image of each individual fibre end along the length of the slit image. A corrector lens is introduced in the vicinity of the image plane to produce a flat field on the film. The entrance slit is rotated slightly about the optical axis of the system to prevent overlap of the images of the spectra.

Constant optical performance and resolution is obtained over the whole spectral range being recorded.

Discrete frames of the spectra are recorded by introducing an equal and opposite movement of the slit, as seen by the collimating mirror, which compensates for the image movement of the photographic film caused by the drum rotation during recording. The slit movement is virtual, and is achieved by directing the emergent light from the multi-channelled slit to the collimator via a number of reflecting facets as shown in Fig. 3. Ninety of these optically worked surfaces are equally disposed around the circumference of an optical polygon. The incident light from the slit is directed and reflected from each of these polished surfaces as the polygon rotates about its vertical axis. The polygon is driven in synchronism with the recording drum through a 10 : 1 gear ratio.

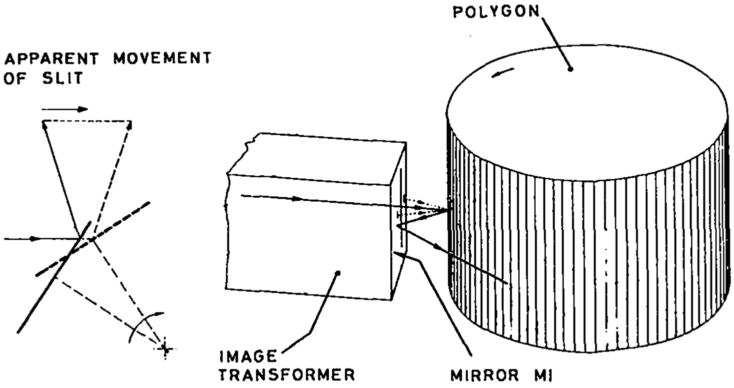

Fig. 3 – Synchronisation mechanism

Since the polygon has to rotate continuously at 70,000 r.p.m. it is limited in size to 2.8 inches external diameter. This means that the width of each facet approximately 2.5 millimetres, which is necessary to maintain an F/3 aperture at the film. To retain maximum aperture of the light beams being reflected from the facets of the polygon, and to avoid excessive overlap in time of the frames being recorded at the film, a geometry of near normal incidence and reflection at the facets is essential. This however, has resulted in an additional reflection at the surface (M 1) of the slit end of the image transformer to redirect the light beam from the slit and polygon towards the collimating mirror. The Framing Drum Spectrograph described has been designed, and is being produced at Aldermaston.

I would like to thank Mr. I. MADDOCK for his encouragement and Mr. R. ALLISON for his able assistance during the design and development of the instrument. Acknowledgement is also made to the Director of the Atomic Weapons Research Establishment for his permission to publish this paper.

Summary

A continuous access, framing spectrograph capable of photographically recording spectra of spatially resolved images of rapidly moving events and light sources.

The instrument has a F/3 reflecting optical system and uses a 600 lines/mm plane grating as the dispersing element.

A resolution of 5 Å and a dispersion of 50 Å/mm is expected over the spectral range of 3,000 Å to 9,000 Å which is recorded on a continuous length of 5" wide photographic film. The film is held in a darkroom loaded cassette which is rigidly attached to the inside diameter of a 16" diameter rotating drum.

The drum rotating at approximately 7,000 RPM is synchronised with an optical image movement compensator, and a recording frequency of 110,000 frames per second is achieved. A frame is composed of the spectra of the image of the spatially resolved event. Spatial resolution is accomplished by means of a fibre optic image transformer, the field of view covered by the objective lens being reduced to a multi-element array which becomes the entrance slit of the framing spectrograph.

Résumé

Spectrographe à vues cinématographique, à entrée continue, capable d'enregistrer par photographie les spectres des images séparées, spatialement, d'objets et de sources lumineuses en mouvement rapide.

L'instrument possède un système optique par réflexion à F/3 et utilise un réseau plan de 600 traits/mm comme élément dispersif.

On peut espérer une résolution de 5 Å et une dispersion de 50 Å/mm dans le domaine spectral 3000 Å à 9000Å enregistré sur un film de 5 pouces de large. Le film se trouve dans une cassette, chargée dans une chambre noire, et il est attaché rigidement à la paroi interne d'un tambour tournant de 16 pouces de diamètre.

Le tambour qui tourne à environ 700 t/min est synchronisé avec un compensateur optique du mouvement de l'image, et on arrive à enregistrer 110 000 vues par seconde. Une vue est entièrement constituée par le spectre de l'image de l'objet résolu spatialement. La résolution spatiale est obtenue au moyen d'un transformateur d'images à fibres optiques, le champ couvert par l'objectif étant réduit à un dispositif comprenant plusieurs éléments. Ce champ constitue ainsi la fente d'entrée du spectrographe à vues cinématographiques.

Zusammenfassung

Es wird ein ununterbrochen aufnahmebereiter Bildreihenspektrograph beschrieben, in dem zuerst eine räumlich zerlegte Abbildung der untersuchten sich schnell bewegenden Vorgänge oder Lichtquellen hergestellt wird und dann die Spektren der einzelnen Bildelemente photographisch registriert werden.

Das Gerät besitzt eine f/3-Spiegeloptik und verwendet ein ebenes Strichgitter mit 600 Linien/mm als dispergierendes Element. Ein Auflösungsvermögen von 5 Å und eine Dispersion von 50 Å/mm wird über den Spektralbereich von 3000–9000 Å erwartet. Dieser Bereich wird zusammenhängend auf einem 12,5 cm breiten Film registriert. Der Film liegt in einer im Dunkelraum geladenen Kassette, die fest an den inneren Umfang einer Drehtrommel mit 40 cm Durchmesser angebracht wird.

Die mit 7000 Umdrehungen/min rotierende Trommel ist synchronisiert mit einem die Bildbewegung optisch ausgleichenden Element. Als Aufnahmefrequenzen werden 110 000 Bilder/sec erreicht. Jedes Bild setzt sich zusammen aus den Spektren der Bildelemente der räumlich aufgelösten Abbildung des untersuchten Vorgangs. Die räumliche Auflösung wird in einem Faseroptik-Bildtransformator erreicht, durch den das vom Objektiv erfaßte Gesichtsfeld in eine Vielzahl einzelner Elemente zerlegt wird, die dann in linearer Anordnung den Eingangsspalt des Bildreihenspektrographen bilden.

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