Design and Application of a High-Speed Time-Resolving Spectrograph

PAPER F—3

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The design and construction of a time-resolving spectrograph having a time resolution of 0.02 μsec and a wavelength resolution of 3 A are described. This instrument was built by the Beckman & Whitley Corp. for the Poulter Laboratories of Stanford Research Institute for use in the study of high-explosive phenomena. Calibration of the instrument by use of a standard tungsten filament lamp is described.

This calibration included a study of the intermittency effect at exposure times of the order of 0.02 μsec. Examples of the application of the instrument to the measurement of high temperatures produced by high explosives are given. The illustrations include temperature measurements of detonation fronts in explosives and explosively induced shock waves in air and argon. Also included are studies of "Mach Detonation Events" produced by converging ordinary detonation fronts, exploding bridge wires and high-energy spark and arc discharges.

IN THE FIELD of explosive research instrumentation there are many ingenious cameras designed to record various types of information from a detonating explosive. Framing cameras, streak cameras and flash x-ray units have been developed to a point where it is possible to obtain much hitherto unobtainable information about the processes taking place in a few millionths of a second during a detonation. Until recently, it was not possible to investigate the spectral distribution of the light being emitted by such experiments during the actual detonation since ordinary spectrographs would record all the light emitted by the shocks and smoke of the later stages on top of the record of the detonation itself. For some special applications, a smear camera could be added to a spectrograph in order to obtain time-resolved records of such detonations. However, since the spectrograph and smear cameras were usually not designed as a unit, the design could not be optimized for the type of experiment being performed. Accordingly, the Poulter Laboratories of Stanford Research Institute requested Beckman & Whitley, Inc., to construct a time-resolving spectrograph which would be more usefully designed for high-explosives research, with particular emphasis on temperature determination by radiation distribution measurement.

Design

The design of the spectrograph was chosen to provide the maximum photographic aperture possible commensurate with reasonable wavelength resolution and time resolution. The limiting aperture of all the optics used is $f/2.5$ and the grating used is of a highly efficient design with rulings blazed for maximum reflection into the first-order visible spectrum.

Figure 1 shows the basic optical layout of the spectrograph. The object under study is imaged by the objective lens on the entrance slit which limits the vertical dimension of the area observed. This slit is at the focal plane of the collimating lens which is an $f/2.5$, 12-in. Kodak Areo-Ektar. The parallel light transmitted by this lens falls upon a 600 lines/mm Bausch & Lomb "Certified Precision" replica grating ruled 4 in. square on a 6-in. diameter blank. The spectrally dispersed light from the grating is refocused by the same lens via a front surface mirror onto the entrance slit of the smear camera. This slit limits the horizontal dimension of the area observed by the spectrograph and reduces a line spectrum to a row of dots. The smear camera refocuses the spectrum appearing on this slit via a rotating mirror onto the film. Figures 2 through 5 show photographs of the various parts of the spectrograph.

Various adjustments are available for proper alignment of all the components, such as the entrance slit, the horizontal grating angle, the front surface mirror and the second slit alignment. In addition, the operating controls include those for objective focusing, with a periscope microscope to check the position and sharpness of the image, grating rotation to choose the wavelength region being recorded and a synchronizing coil adjustment to allow for the delay time in the shot. A mercury-arc lamp is included in the camera, and the spectrum from this lamp can be recorded on the film via the optics to be used for the experiment. These lines then provide a wavelength scale on the film record.

The wavelength resolution achieved by this instrument is approximately 3 A and the time resolution is approximately 0.05 μsec at maximum speed. When recording at maximum speed with a 150-micron slit on Kodak Tri-X Film which is developed in GE X-Ray Developer for 15 min at 68 F, the object under study must emit approximately 10^{16} erg sec^{-1} cm^{-2}/cm of wavelength range in order to achieve a density of 0.1 above fog at a wavelength of 0.5 micron.

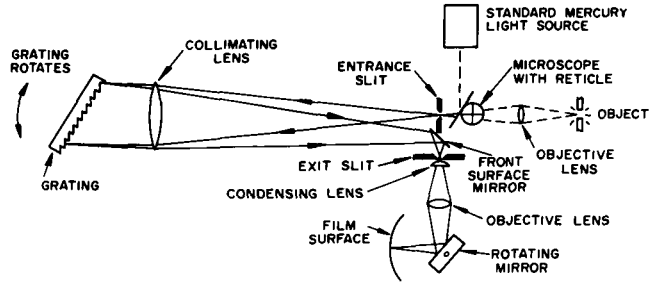

Fig. 1. Basic optical layout of time-resolving spectrograph.

Presented on October 19, 1960, at the Fifth International Congress on High-Speed Photography in Washington, D.C., by Donald Baker Moore and John K. Crosby (who read the paper), Stanford Research Institute, Menlo Park, Calif.

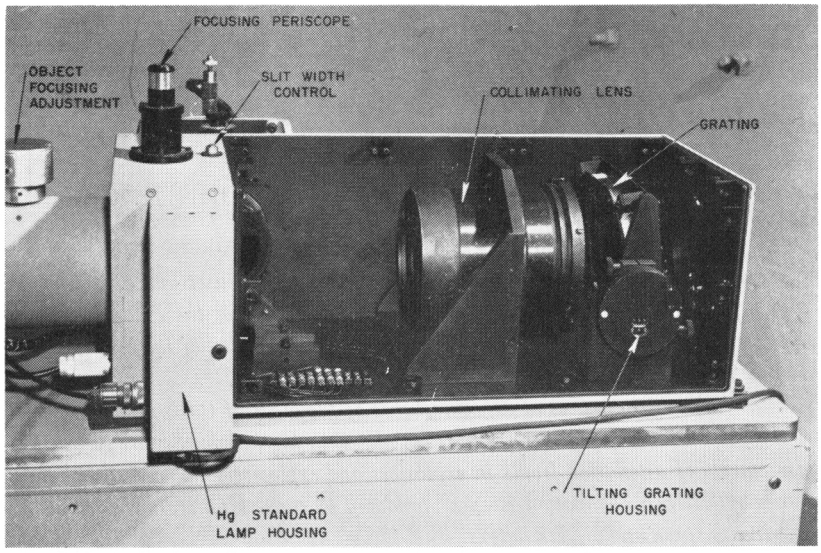

Fig. 2. General view of spectrograph with cover removed.

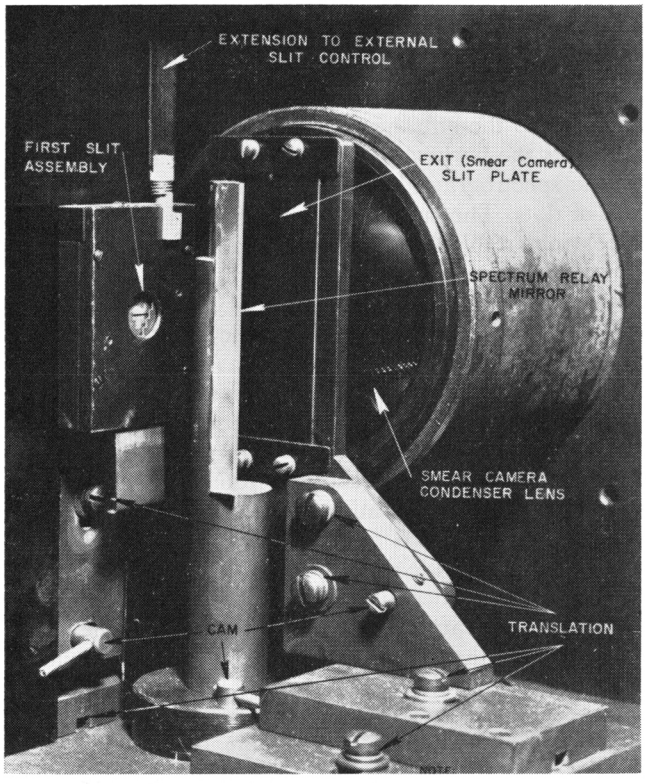

Fig. 3. Detail of first and second slit assembly.

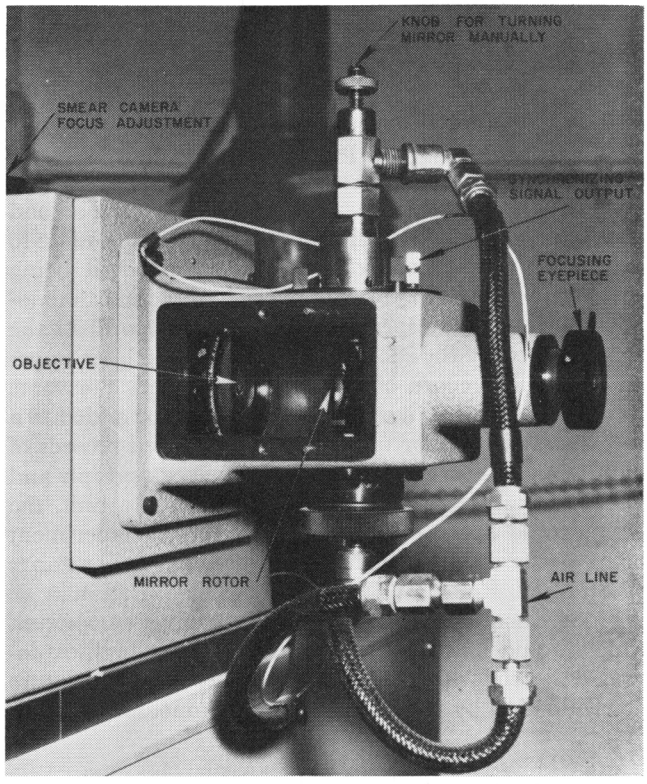

Fig. 4. Smear camera with film cassette removed.

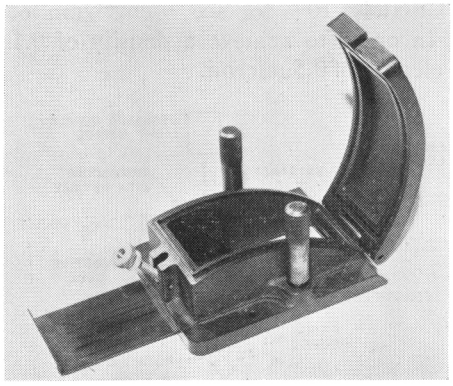

Fig. 5. Film cassette.

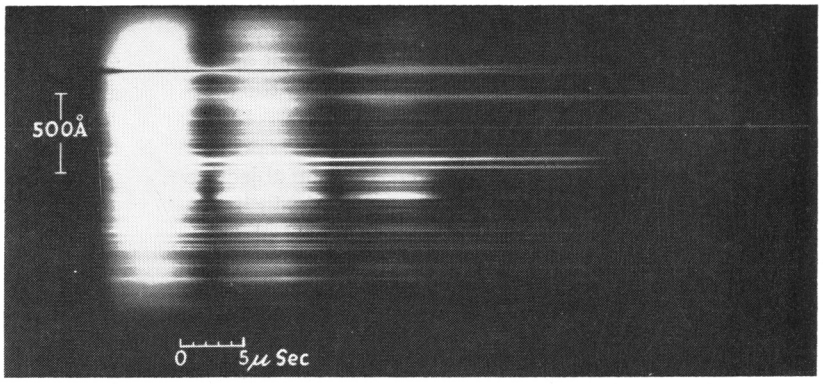

Fig. 6. Record produced at end of coaxial cable dipped in $NaHCO_3$ and pulsed with 5000-v detonator output.

Calibration

The wavelength calibration of the instrument is accomplished using either the built-in mercury source or, if more lines are needed, an exterior Geissler tube source. When this is done the dispersion is found to be 0.0962 micron/cm on the film with a variation of approximately 0.8% between the points with largest and smallest dispersion.

The writing speed of the instrument has not been checked experimentally since an accurate determination of times has not been necessary to date. The smear camera was designed to have exactly $\frac{1}{2}$ the radius of another smear camera already in use at these laboratories and hence, the writing speed is probably quite close to $\frac{1}{2}$ the writing speed of this camera, or 1.905 mm/μsec at a mirror speed of 2000 rps.

The major calibration problem with instruments of this type is in connection with intensity determinations. A theoretical calculation of the transmission of the system as a function of wavelength, mirror angle, grating angle and object distance could be made, but since there are so many optical elements and surfaces it would be highly inaccurate. In addition, to apply the results to the determination of intensity from the trace recorded on a piece of film, the spectral sensitivity of the film would also have to be known. Accordingly, it was decided to calibrate instrument and film together as a unit, using a source of known spectral intensity distribution.

If the shot fired and the standard source used are set up at the same distance from the camera and the grating angle is kept constant, then the only remaining variables will be wavelength and mirror angle. Ideally, an extremely bright source of known intensity vs. wavelength characteristics should be recorded on a film at the same position that the shot will be recorded so that only wavelength variations in the D-log E curve would remain. However, since the source of known spectral distribution used is a tungsten filament which is not bright enough to record on a single sweep, multiple sweeps over the entire film length are used and the record is analyzed only in the areas where the shot record appears. This approach to the problem ignores one important effect of the short exposures and high intensities used to record the shot, namely the reciprocity failure of the film under these conditions. Because the calibrating exposure is made up of a large number of very short exposures, it might be expected to exhibit the same reciprocity failure as the single short exposure made for the shot record. Unfortunately, an intermittent exposure of this sort will exhibit the same loss in film sensitivity as a single flash exposure only when the number of intermittent flashes is kept very low, well below 100, for example. Since the shortest exposure used in the standardizing procedure here has about 3000 flashes, it will produce an effect identical to a continuous exposure of the same average intensity.

Kodak Pamphlet No. P-32 shows that Tri-X film, when developed for 10 min. in Kodak Rapid X-Ray Developer, has an approximate sensitivity loss of 36% when exposed for times of the order of 1 μsec. Therefore, as an approximate correction, all intensities derived from shots reported here have been corrected by this factor and it is hoped that the results obtained will not be too inaccurate from this cause.

The procedure followed was to expose the film with the mirror running at 200 rps to a source consisting of a ribbon filament bulb operating at a measured temperature of 2140 K. Five exposures were made on separate pieces of film with a progressive doubling of the exposure time for each successive exposure. These films were then measured on a Welch Densichron densitometer using an aperture 0.6 mm in diameter. The density vs. wavelength was measured on each film at time positions corresponding to those at which records of shots had appeared. From this information and the assumption of blackbody radiation from the tungsten a plot of density vs. surface intensity multiplied by time was made for a variety of wavelengths. These curves were then used to determine the intensity corresponding to a given density in a shot record.

Applications

Figure 6 shows a typical record obtained when the end of a coaxial cable which had been dipped in sodium bicarbonate is pulsed with a 5000-v detonator output. This sort of record shows the line spectrum produced by the spark and arc formed at the cable end. Note also the oscillation of the discharge after the initial pulse.

Figure 7 shows the setup used to observe the shock induced in either air or argon by a detonation in Composition B-3. It is assumed that the Mylar does not affect the light from the shock wave, although in some shocks there appears to be an effect when the shock wave begins to intersect the Mylar. Figure 8 shows the record obtained from such a setup when air is used and shows the brightening which occurs when the shock hits the Mylar. The spectral intensity distribution deduced from this record corresponds to a brightness temperature of 12,500 K. The temperature at the time of reflection from the Mylar is 31,000 K.

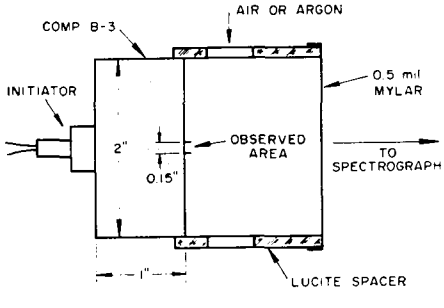

Fig. 7. Setup for observing shock induced in either air or argon by a detonator of Composition B-3.

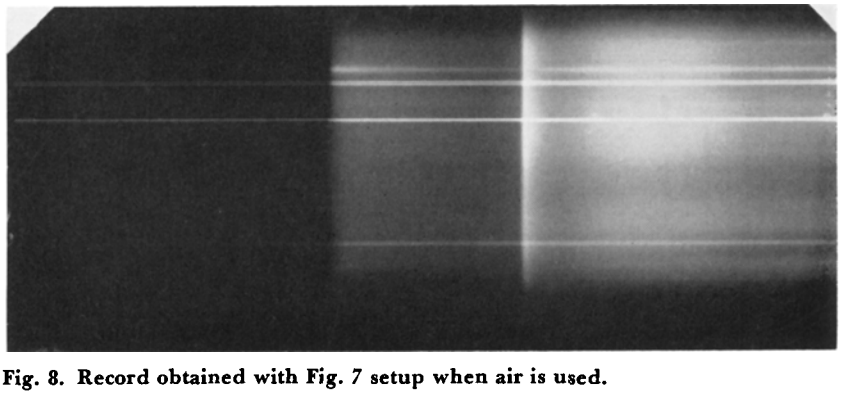

Fig. 8. Record obtained with Fig. 7 setup when air is used.

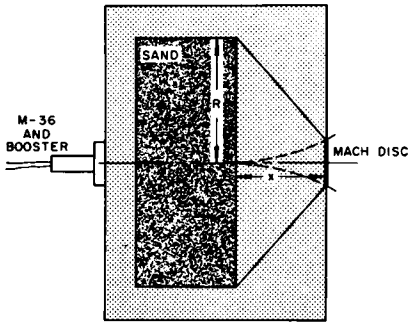

Fig. 9. Explosive design used to obtain a Mach disc, a high-velocity, high-pressure detonation phenomenon.

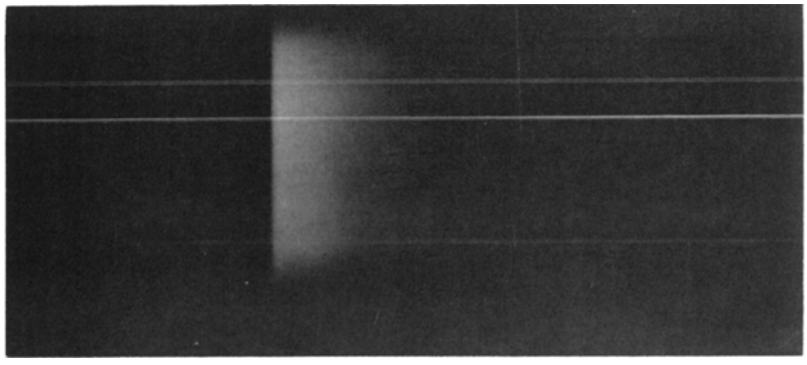

Fig. 10. Record obtained with Fig. 9 design.

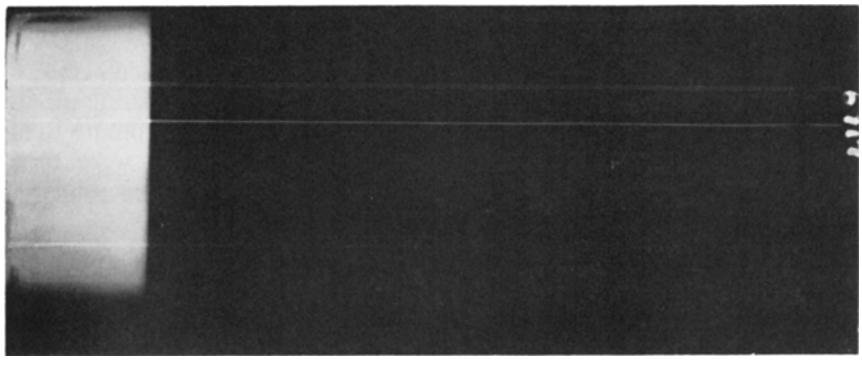

Fig. 11. Record of extremely bright light obtained with argon shock.

Figure 9 shows the explosive design used to obtain a high-velocity, high-pressure detonation phenomenon known as a Mach disc. The barrier forces the detonation to travel around it, and when the subsequent converging detonation on the other side of the barrier meets, a small area at the axis will experience an extremely high pressure. If the spectrograph is lined up so that this area fills the aperture, the shock wave observed should be at a much higher pressure and temperature than that from an ordinary detonation. Figure 10 shows the record obtained from this shot. Since the light was expected to be considerably brighter than that observed in the ordinary detonation shot, the first slit was closed down by a factor of $2\frac{3}{4}$, resulting in the lower film density observed here. The spectral intensity distribution deduced from this record corresponds to a brightness temperature of 50,000 K.

It has long been known that argon shocks will give extremely bright light, and Fig. 11 shows the record obtained from such a shock. The brightness temperature here is over 100,000 K, which is probably far more than the actual temperature of the shock. This illustrates that in at least this case the calibration is not accurate enough at high densities to give reliable temperature determinations.