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

During the Sixth International Congress on High-Speed Photography, Koch and Simon reported on a multi-station shadowgraph system featuring a novel method of projectile detection and shadowgraph triggering§§ which may be useful in some hypervelocity impact work. That same system, now refined and extended, was described again in the Seventh Congress (31). The detection scheme makes use of a microwave Doppler radar arrangement, whose output is supplied to a frequency divider from which the shadowgraph trigger pulses are developed. Trigger pulses are produced, thereby, at projectile positions along the trajectory which are separated precisely by integral multiple microwave half-wavelengths. The authors report relative scatter in velocity measurements of the order of only 5×10^{-4}. Unlike the Gehring and Christman "pre-impact computer" already discussed, this system can be relied upon to develop trigger pulses upon projectile arrival at various stations along its trajectory quite regardless of any drag-induced decay in velocity. This system is, however, considerably more complex than the one which was described by Gehring and Christman.

Some of the problems found in the photography of exploding wires are similar to those which arise in the recording of hypervelocity impact phenomena. Time scales are similar; the exploding wire is enveloped in an opaque, luminous sheath; and there is need to image minute particles. Chace, Levine and Fish reported an x-ray technique used in the study of exploding wires (44), and the results are encouraging to those who use radiography in impact diagnostics. Working with a flash x-ray system having an exposure duration of 30 ns, the authors compared radiographic images of exploding wire phenomena with back-lighted photographs made using visible light (from an exploding metal foil) and a Faraday shutter camera. It is readily seen from the comparisons that the x-ray technique records the cloud of exploding wire material while the photography records a misleading larger and earlier luminous shroud. Neither the form nor the dimensions of the cloud of wire material are interpretable photographically.

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

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

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

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

Summary of Papers Dealing With X-Ray Techniques

By J. P. BARBOUR

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

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

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

Flash X-Ray Discharge Mechanisms

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

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

The tube voltage is assumed to be given by the equation

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

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

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

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

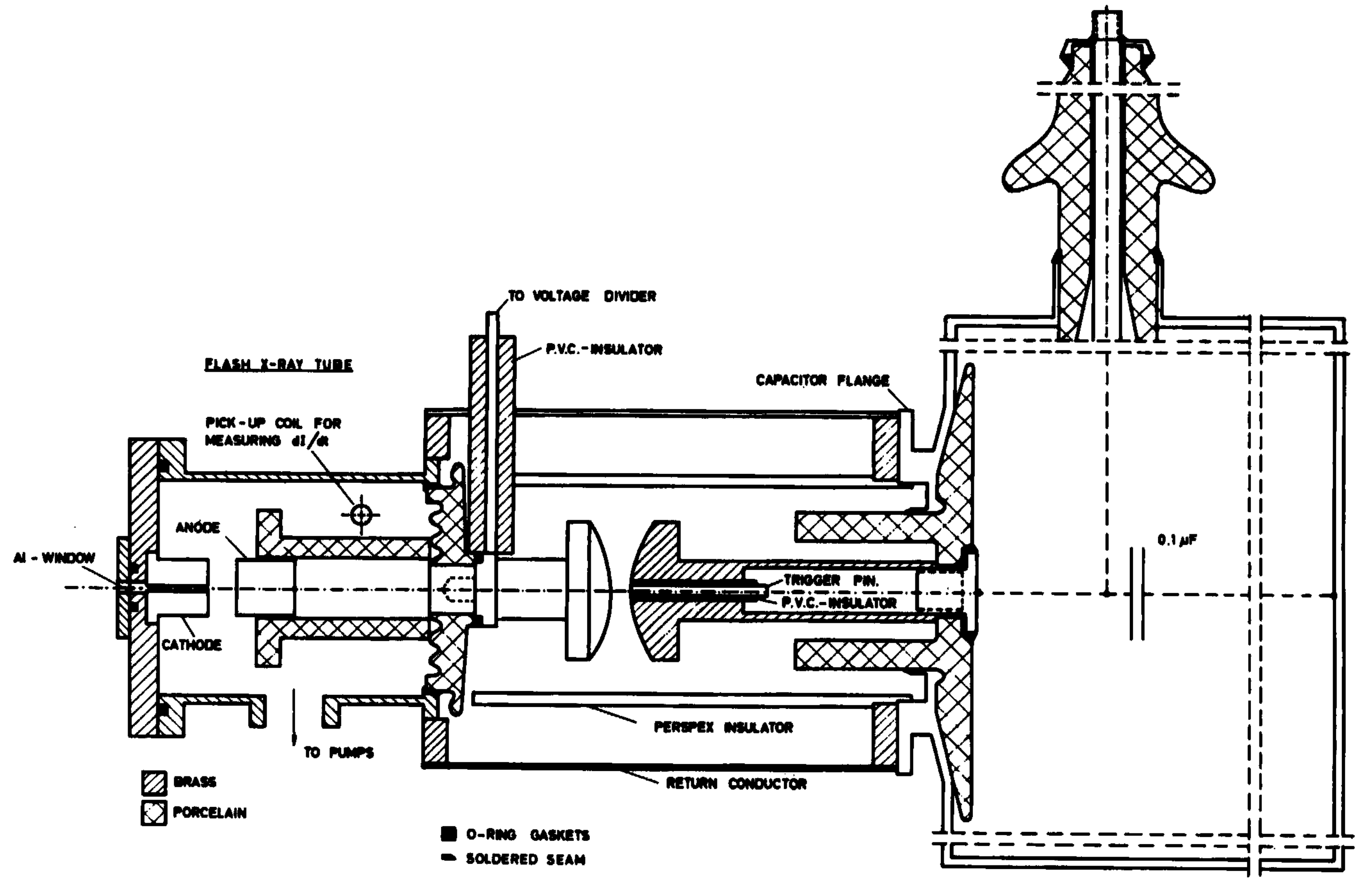

Fig. 1. Diagram of the coaxial discharge system and flash x-ray tube.

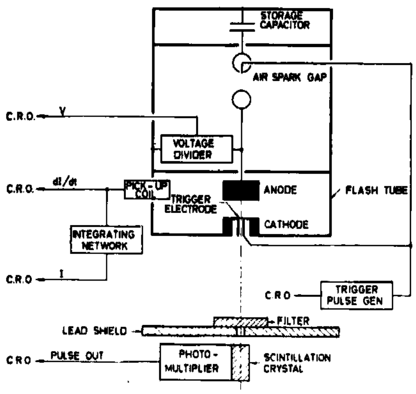

Fig. 2. Schematic diagram showing the discharge system and instrumentation.

and L which were calculated from the experimental data.

The discharge process can be divided into two consecutive phases: the first characterized by constant voltage, and the second by a fluctuating voltage. In many cases the voltage increased to a value higher than the initial voltage during the second phase. Time correlations between voltage, current, and x-ray output were obtained. Both the current and x-ray output were very small during the first phase, and increased rapidly thereafter.

The x-ray output pulse shape was also obtained with appreciable filtering between the tube and photomultiplier, and it was found that the harder components of the x-ray beam occurred when the di/dt oscillations indicated pronounced dips. A crystal spectrometer was used to determine the minimum wavelength of the radiated photons. By adjusting the spectrometer it was determined that photons with energy 50% greater than the charging voltage were obtained in short duration bursts corresponding in time to dips in the di/dt wave.

These data agreed well with the pinch theory which attributed the higher voltage peaks to pinch effects in the plasma with consequent large terms involving $L\ di/dt$ and $i\ dL/dt$, where L is the inductance in the diode gap, and i is the beam current.

Equipment and Systems

Paper 42 described a new 2 million V flash x-ray machine which utilizes a coaxial discharge system in a metal enclosed, gas pressurized case. The complete 2 mV radiographic system is shown in Fig. 5. The design minimizes the radiation of electrical noise, which otherwise could interfere with auxiliary instrumentation, and the unit is completely sealed against dust and watervapor to eliminate operating instabilities arising from such contaminants. The pulse length has been reduced to 20 ns to minimize motion blur.

The high voltage pulse generator is a modified Marx-surge unit in which pulse forming networks, rather than capacitors, are used for the electrical storage elements. The output pulse thus more closely approaches the form of a square wave which is desired for most applications. The lines are charged in parallel and then switched by pressurized spark gaps to form a series electrical network. There are 160 switched networks so that the dc charging voltage is only 30 kV.

Two tubes are available for use with this system. The model 543 is an x-ray tube with a 5-mm source size, and the model 545 is designed so that the electron beam can be extracted through a thin window into air. The 5000-A beam can thus be either used directly for radiation effects studies, or may be allowed to impinge on a tungsten target to form x-rays. The x-ray penetration characteristics of the system are shown in Fig. 6. With fast films and intensifier screens single pulse exposures can be obtained with thick objects. For example, satisfactory exposure can be obtained through 5 in. of steel with a film-to-source distance of 5 ft. Alternatively higher resolution films can be used where less penetration is required in order to reveal fine detail. Figure 6 also shows that a shadowgraph can be obtained with a film-to-source distance of 80 ft. Thus large areas can be covered with a single pulse; for example, the

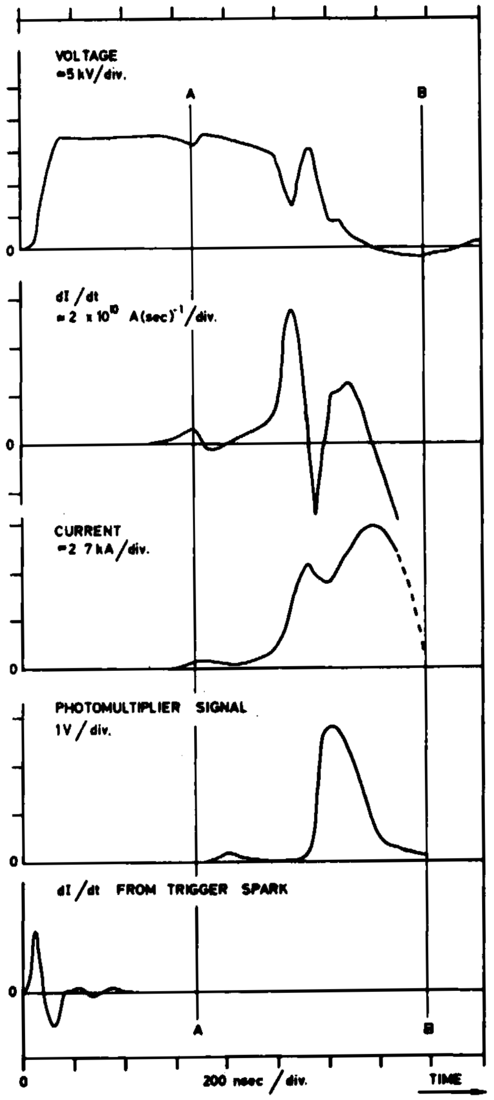

Fig. 3. Oscillograms showing the time variation in voltage, current and x-ray output.

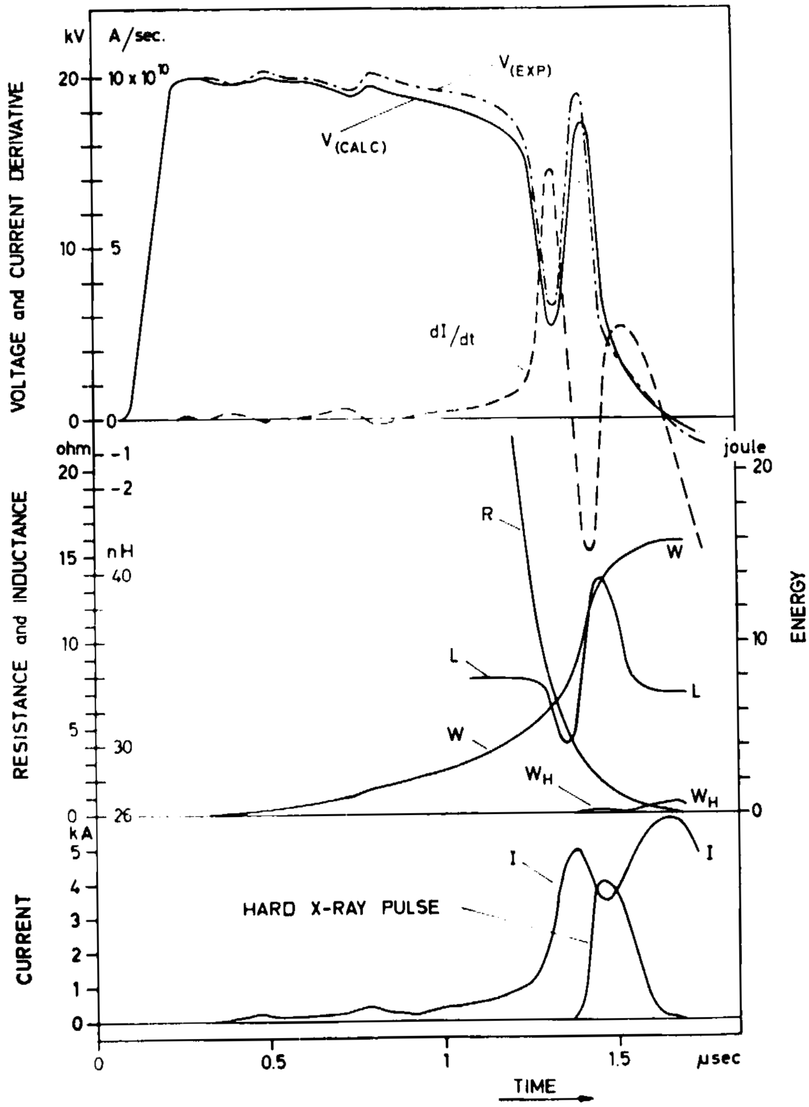

Fig. 4. Flash x-ray discharge characteristics showing both measured quantities (voltage, current, x-ray output) and calculated values of energy, resistance and inductance.

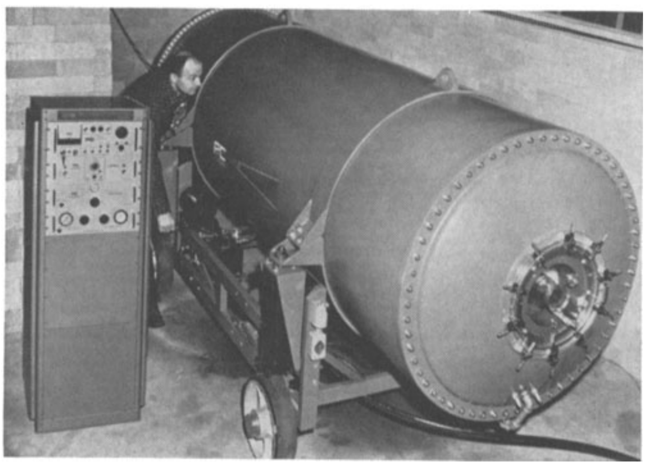

Fig. 5. Complete 2 MV pulser system and control panel.

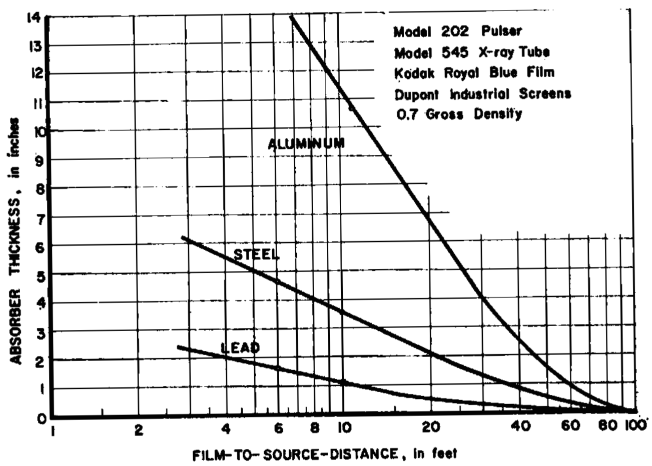

Fig. 6. Penetration characteristics obtained with the Model 545 tube with an external transmission target.

trajectories of shrapnel fragments from a bomb explosion.

The reproducibility of the system is illustrated in Fig. 7. Data were obtained over a three month period, and gaps in the curve occur because during some experiments the x-ray dose was not monitored.

A new cineradiography system (43) was also described with which x-ray motion pictures can be obtained with a single x-ray tube at frame rates up to 10^5/s. The system operates at 150 kV and 20 J/pulse. The pulse length is 70 ns and the x-ray source size is 2 mm. The

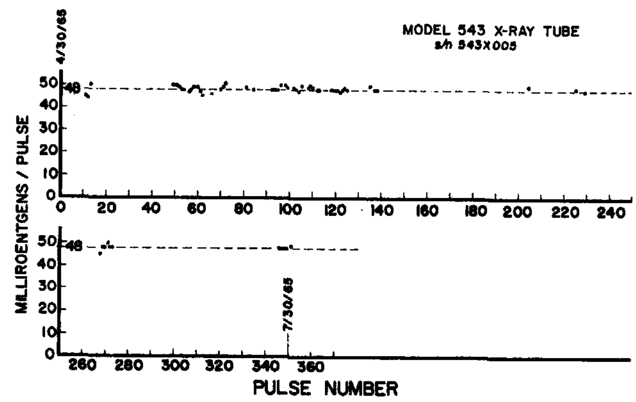

Fig. 7. Graph of measured x-ray dose vs. pulse number illustrating reproducibility.

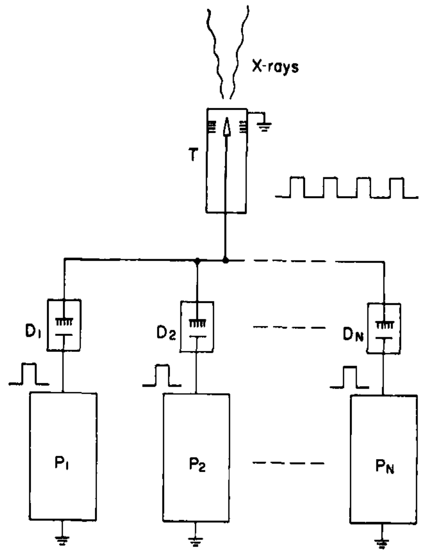

Fig. 8. Schematic diagram showing the experimental arrangement used for high-speed cineradiography.

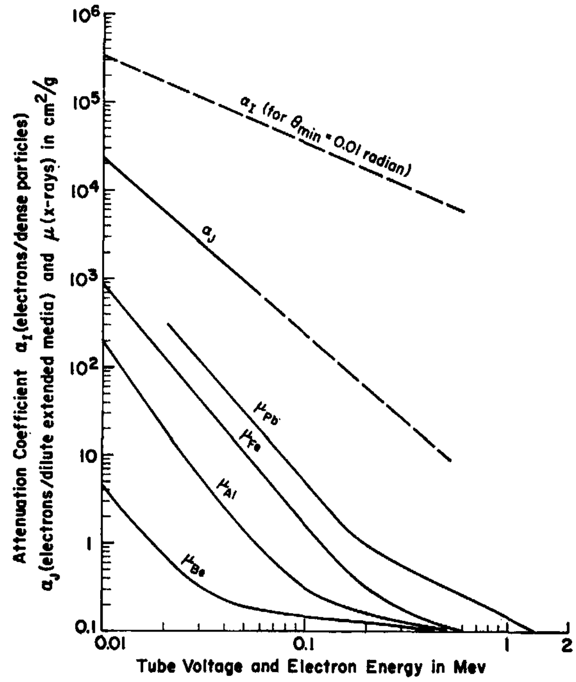

Fig. 10. Graphs showing electron beam attenuation coefficients α_I for thin particles and α_J for extended, tenuous media and x-ray absorption coefficient μ for several materials as a function of tube voltage and electron beam energy in MeV.

system impedance is 70 Ω so that the pulsers, connecting cables and tube heads are completely coaxial to minimize pulse distortion and radiated electrical noise.

The system has been made possible by the development of a new field emission switch tube which will pass the required current of 2000 A in the forward direction and will hold off the peak voltage of 150 kV in the reverse direction. The tube is 1½ in. in diameter and 9 in. in length and fits into an enclosed coaxial tube head.

A schematic diagram of the system is shown in Fig. 8. A train of x-ray pulses is formed by discharging sequentially, several high voltage pulsers through a single flash x-ray tube. The pulsers (P) are shown connected to the single x-ray tube through the switch tubes D. A single trigger pulse initiates the pulsing sequence, and the interpulse interval can be arbitrarily adjusted by variable delay trigger generators.

Figure 9 (see Fig. 10 in preceding report by P. L. Clemens) shows a 3-pulse sequence of a 30.06 bullet, with an initial velocity of 3600 ft/s, striking two lead plates. The three exposures were superimposed on a single film. The trajectory and velocity of the bullet can be obtained from the first two exposures; the third exposure shows the result of the impact and the distribution of target fragments.

Betagraphy

A new method of obtaining a photographic image using a pulsed electron beam was described in paper 41. Small objects of low atomic number material often do not absorb sufficient x-rays to yield a high contrast radiographic image. Since electrons interact strongly with matter, very small amounts of material will significantly attenuate an electron beam, and thus be detected on the image which the beam forms on photographic film. The term betagraphy has been coined to describe this method of image formation. By simultaneous use of both x-rays and an electron beam originating from the same location, observation can be extended to a wide range of object sizes and densities. X-rays will elucidate the more dense portions such as small particles, thin films and gas clouds.

The system described generated an electron beam with a pulse duration of 20 ns, a peak current density of 1000 A/cm², and the beam voltage could be varied from 300 to 600 kV. The beam was extracted from the tube through a thin metal window: a portion of the electron beam was allowed to pass through a limiting aperture and form the betagraph image, and the remainder of the beam struck a tungsten target and generated x-rays.

There is a basic difference between x-rays and electrons from the standpoint of interaction with matter and image formation. With x-rays, absorption and large angle scattering predominates: small angle scattering, where the photon interacts but is still able to reach the detector is a secondary effect. Scattering is the dominant mechanism for removing electrons from the directed beam unless the object thickness equals or exceeds the electron range. The image is thus dependent on both the geometry and scattering coefficients of the objects to be imaged.

Under most conditions of interest an equivalent mass attenuation for an electron beam traveling through matter can be defined. The beam current density at the detector is described by the usual equation:

$$J(x) = J_0 e^{-\alpha\rho x}$$

where J_0 is the incident current density, α is the attenuation coefficient, ρ is the density of the medium and x is the distance traveled in the medium. There are two cases which are important experimentally and which can be treated with available scattering data. First, the case of small particles for which values of α_I are appropriate, and second extended dilute media, like gas, for which values of α_J apply. Graphs of both α_I and α_J are shown as a function of voltage in Fig. 10. X-ray absorption coefficients for several materials are included for comparison. Well defined images of small particles can be obtained with small scattering angles since the total distance of the electron must be scattered from its original path is comparable to the particle radius.

From the data shown in Fig. 10 it may be concluded that, because of the large difference between electron and x-ray absorption coefficients, betagraphy can be used to form sharp images of particles too small to be resolved with flash x-rays. Also gas clouds can be imaged with lower energy electrons, and dense particles can be imaged against a gas background because of the difference between α_I and α_J. An example of the resolution which can be obtained is shown in Fig. 11 (Fig. 4, Clemens). This enlargement shows glass beads from 10 to 50 μ in diameter in free fall. The betagraph was made in a chamber with a pressure of 10^{-2} Torr to minimize air scatter of the electrons.

Simultaneous betagraphs and radiographs can be obtained by allowing a portion of the electron beam to pass through a small aperture in a tungsten plate; the transmitted portion is used to form the betagraph and the remainder of the beam forms x-rays. The two films are placed directly adjacent, and electrons form an image on the front film which has a low exposure index so x-rays do not cause appreciable exposure. The second film has a high exposure index and intensifying screens and is exposed by x-rays.

The ballistics object shown in Fig. 12 (Fig. 5, Clemens) was arranged to provide a wide range of objects, sizes and densities, and to hide part of the event in an optically opaque region in the form of a hollow aluminum cylinder. The betagraph, shown in Fig. 13A (Fig. 6a, Clemens) elucidates the less dense portions: wood (W), wood chips (WC), vapor caused by wood impact (WV), and vapor, presumably lead, released at projectile impact. The radiograph, Fig. 13B (Fig. 6b, Clemens), records the more dense portions; the bullet (B), lead disc (L), lead fragments (F) and aluminum cylinder (A). The use of both x-ray and electrons extends observation to a wide range of sizes and densities; from vapor to solid lead.

Applications of Flash X-Rays

The expansion of exploding wires has been studied using both light and x-rays (44). Data were obtained by both photographing the self luminosity of the wire and by using a second exploding wire as a backlighting source. X-ray shadowgraphs were also made to determine the variation in material density by measuring the absorption of x-rays. The data showed that erroneous values of expansion velocity were obtained using light, and the exploding wire actually is surrounded by an opaque, luminous sheath.

Intense shock waves are encountered, and the x-ray film cassette must be protected to prevent pressure marking of the film. A polyethylene shock attenuator was developed which gave adequate protection to the film cassette, but did not attenuate appreciably the x-ray beam.

A 30-ns x-ray pulse duration was used to minimize motion blur. Since the wire diameter (0.5 mm) was comparable to the x-ray source size, it was necessary to develop a computer program to relate film density to the amount of absorbing material. With the aid of the computer the density of material could be accurately determined as a function of position.

Figure 14 shows the relationship between the data obtained with light and x-rays. During the initial expansion the measured diameter does not depend on the method of obtaining the data. As the expansion progresses, however, the expansion velocities determined with x-rays are appreciably less than the values obtained from measurements using light. Between two and three μs after burst these values differ by a factor of three.

The authors concluded that there is an optically opaque, luminous sheath surrounding the wire which introduces large errors when expansion velocities are measured with light. They also conclude that flash radiography is the most reliable method of measuring accurately the diameter of the exploding wire and determining the actual distribution of material.

In paper 45, Professor Schaafs reported on the use of flash x-rays for measuring the operating characteristics of high power electrical switches. A system was developed for the purpose of observing the operation of liquid filled switches so that fluid flow and the motion of the electrodes could both be studied in detail.

The work reported dealt primarily with high power switches designed for operation at 6000 V, but the results are valid for higher voltage operation. The flow of the liquid dielectric caused by motion of the switch contacts was studied both with and without electrical loading of the switch. Of particular importance is the cavitation which occurs due to rarefaction of the dielectric when motion of the electrodes causes propagation of waves in the liquid. The dielectric strength of the medium can be undesirably reduced by excessive cavitation, and this can lead to electrical breakdown in the switch.

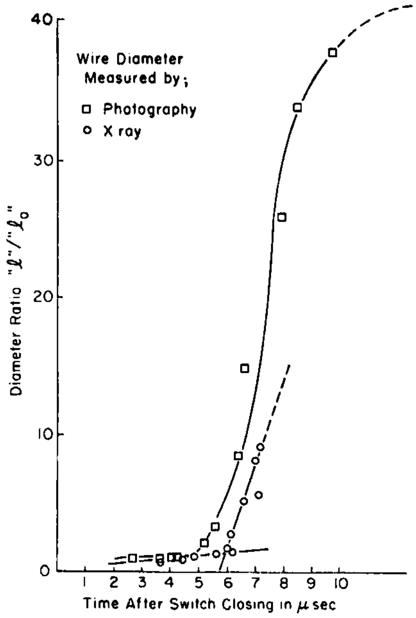

Fig. 14. Graph showing the expansion of an exploding wire as measured both with light and with x-rays.

The flow and cavitation were initially studied when the switch was actuated without an electrical load; this data was then correlated with radiographs taken when the high voltage was applied. The latter radiographs show where arcing and vaporization occur. The switch design can thus be evaluated and changes can be incorporated to improve performance and life.

An application of high-speed cinefluorgraphic techniques was described by Ohlsson, et al., (37). They used frame rates of 270 and 540 frames/s to study the flow of blood in the left heart and aorta. The flow patterns were determined by following the motion of 0.5 to 1 mm particles of iodized oil which were recorded with the aid of continuous x-rays, an image intensifier and continuously running 16 mm cinefilm.

In addition the physiological heart parameters such as blood pressure, left ventricular pressure, phonocardiogram electrocardiogram, intravascular phonorecordings, and electromagnetic flow meter recordings were projected on the back of the continuously running cinefilm. This technique greatly improves the accuracy of time base correlations among the important physiological parameters involved in the operation of the heart as the flow is involved.

Image intensifier systems are used to obtain adequate film exposure with the x-ray beam intensity which is available in the present apparatus. Operation with two high-speed cameras and two image intensifier systems has also been successful, and has resulted in further data being obtained on the fast movement of blood.