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Final Technical Letter Report on NSF Program

HIGH-SPEED CINERADIOGRAPHIC EQUIPMENT FOR BIOSCIENCES RESEARCH

Grant No. ENG 75-22768

Grant Period: 10-15-75 to 3-31-77

Report to:

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16. Abstract

Primary objectives of this project were: 1) to complete the development and construction of a high-speed x-ray cinematographic system for use in biomechanics research, 2) to determine its operational characteristics in application, and 3) to phase the system into on-going biomechanics research programs at the Highway Safety Research Institute. This system consists of a high-speed 16-mm motion picture camera which views a 2-inch diameter output phosphor of a high-gain four-stage, magnetically focussed image intensifier tube, gated on and off synchronously with shutter pulses from the motion picture camera. A lens optically couples the input photocathode of the image intensifier tube to x-ray images produced on a fluorescent screen by a smoothed direct-current x-ray generator. The system is adaptable to a variety of experimental configurations because fluorescent screen size and type can be relatively easily and inexpensively changed.

High-speed x-ray cineradiographs at 1000 frames per second have been obtained of biological and non-biological materials during impact events. Image quality in terms of contrast and resolution has been found to be strongly dependent on judicious introduction of contrast media and targeting material in specimens under investigation. The primary objectives of this project have been successfully accomplished.

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SUMMARY

Primary objectives of this project were: 1) to complete the development and construction of a high-speed x-ray cinematographic system for use in biomechanics research, 2) to determine its operational characteristics in application, and 3) to phase the system into on-going biomechanics research programs at the Highway Safety Research Institute. The system consists of a high-speed 16-mm motion picture camera which views a 2-inch diameter output phosphor of a high-gain four-stage, magnetically focussed image intensifier tube, gated on and off synchronously with shutter pulses from the motion picture camera. A lens optically couples the input photocathode of the image intensifier tube to x-ray images produced on a fluorescent screen by a smoothed direct-current x-ray generator. The system has been found to be adaptable to a variety of experimental configurations because its fluorescent screen size and type can be relatively easily and inexpensively changed. The principal item required for completion of the system was a suitable x-ray generator, capable of producing a relatively steady beam intensity

of x-rays, without the usual rising and falling from zero of x-ray intensity associated with half or full wave rectified x-ray generators. This was accomplished by procurement of a conventional x-ray generator fitted with high-voltage smoothing capacitors across the secondary winding of the high-voltage transformer, which supplies the high anode potential to the x-ray tube. Ripple on the smoothed full wave rectified output is reduced to about 8% at radiographic factors most often used in biomechanics applications at HSRI, determined by measurement with a fast scintillator and photomultiplier tube. The x-ray generator obtained and the synchronously gated detector portion of the system function successfully. Input screen sizes have been varied between 18 inches down to 4 inches in various applications.

High-speed x-ray cineradiographs at 1000 frames per second have been obtained of biological and non-biological materials during impact events. Image quality in terms of contrast and resolution has been found to be generally good, and strongly dependent on judicious introduction of contrast media and targeting material in specimens under investigation. The primary objectives of this project have been successfully accomplished.

Operation and Performance of the High-Speed Cineradiographic System

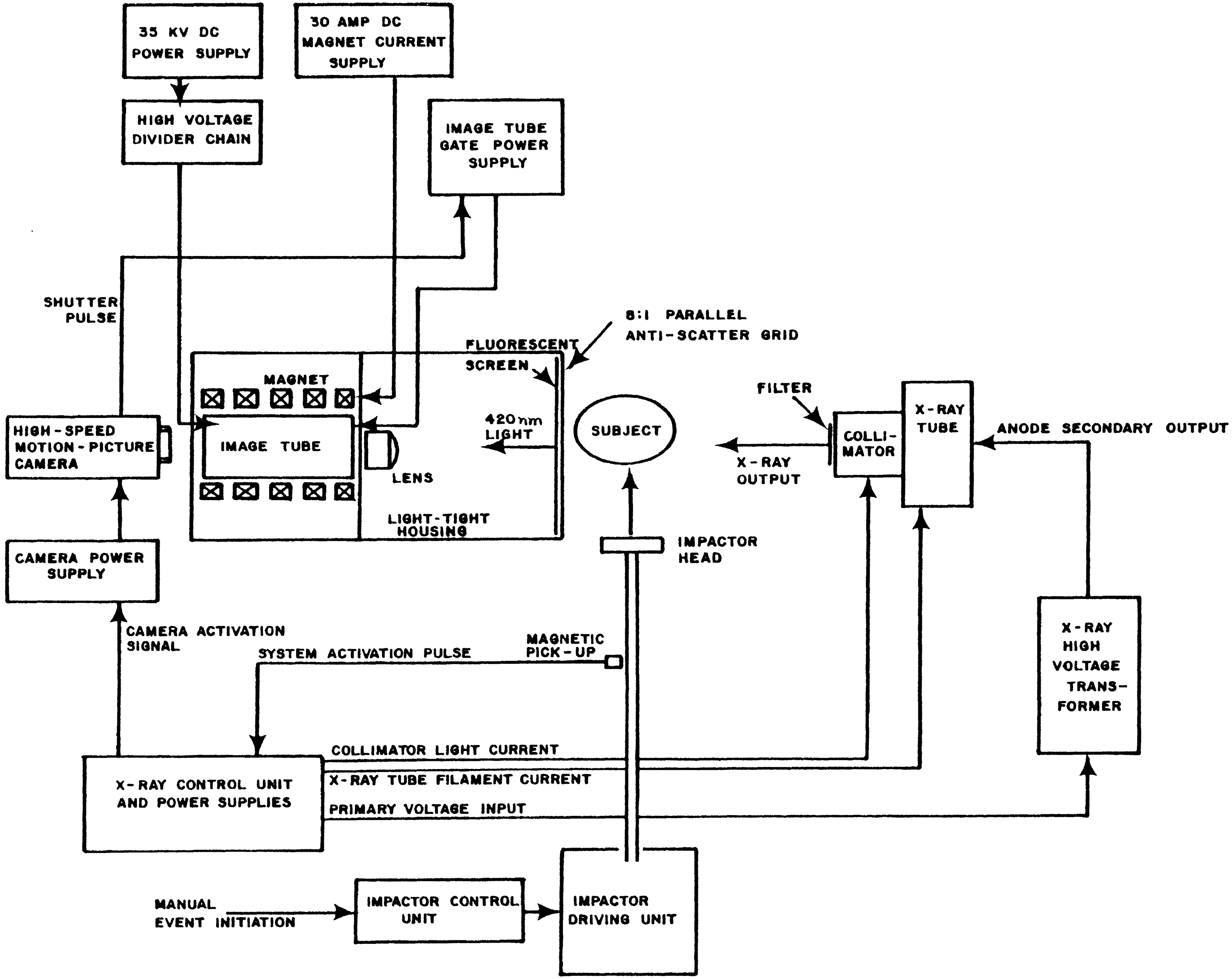
Its method of operation is as follows: an x-ray fluorescent screen shadowgraph of an impact event is imaged by the objective lens onto the input photocathode of the image intensifier. The x-ray shadowgraph on the fluorescent screen varies continuously in spatial distribution and in time. When the camera shutter is in an open position, the image tube is turned on to allow image light amplification, and when the shutter is in a closed position, the image tube is turned off. This procedure for synchronously gating the image tube with the camera was adopted to 1) reduce noise integration in the output phosphor, 2) to lower the duty cycle of tube operation to allow for higher x-ray input for comparatively thick biological material as encountered in human cadavers, and 3) to protect and conserve the image intensifier tube in general from drawing current when no information is being transmitted to recording film.

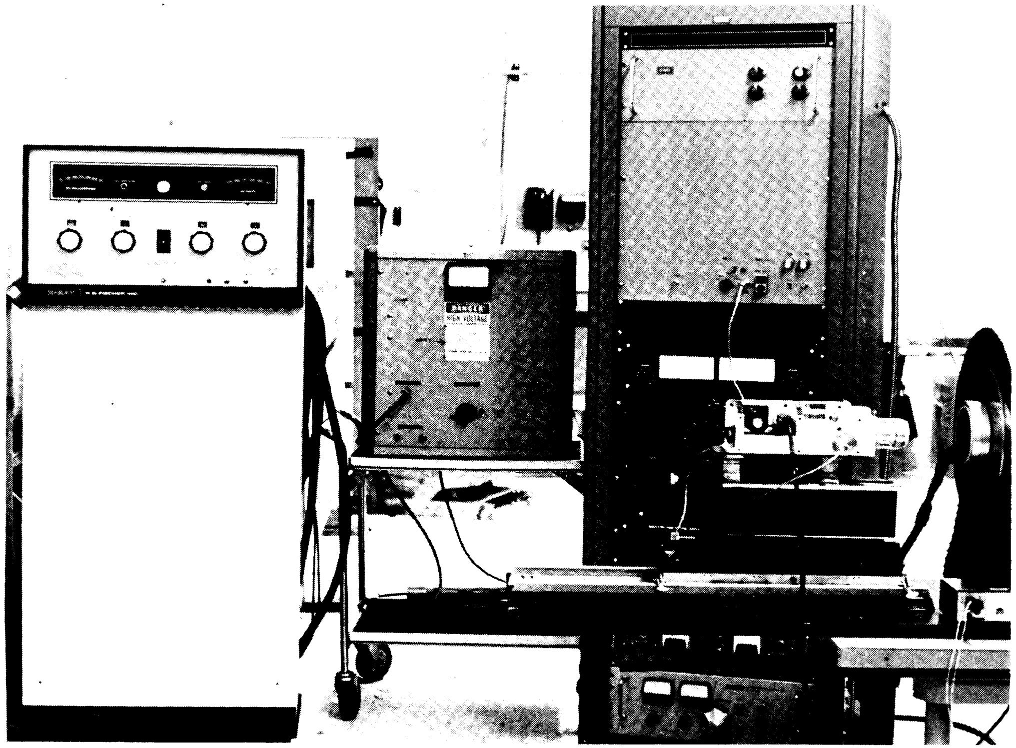
A schematic diagram of a representative impact experiment with application of the system is shown in Figure 1. Activation of the impactor driving unit starts an automatic sequence of timed events which includes x-ray turn-on, motion picture camera start, gated image intensifier tube operation in synchronization with the camera shutter, the impact event, and shut-down of the system, all occurring in approximately 200 ms. A magnetic pick-up element senses onset of the impactor head motion and provides a system activation pulse to the x-ray control unit. The x-ray control unit then distributes signals to the x-ray generator and high-speed motion picture camera, which then initiates image intensifier tube operation in gated mode.

Components of the system are shown in Figures 2(a) and 2(b); Figure 2(a) shows the x-ray control unit at the left, the d-c high voltage image intensifier tube accelerating potential power supply on the cart, the electronics contained in the cabinet at the right for the operation of the image intensifier, and, in front of the electronics cabinet, the structure of the output section of the image tube viewed by a high-speed motion picture camera. Figure 2(b) shows the x-ray head and collimator mounted on a fixture which permits lateral, vertical, and longitudinal displacement. Beneath the x-ray head are shown a 480 to 240 volt, 37.5 kVA transformer and the high voltage transformer which supplies d-c voltage to the x-ray tube anode. All of these components are mobile, to enable set-up in different HSRI laboratories.

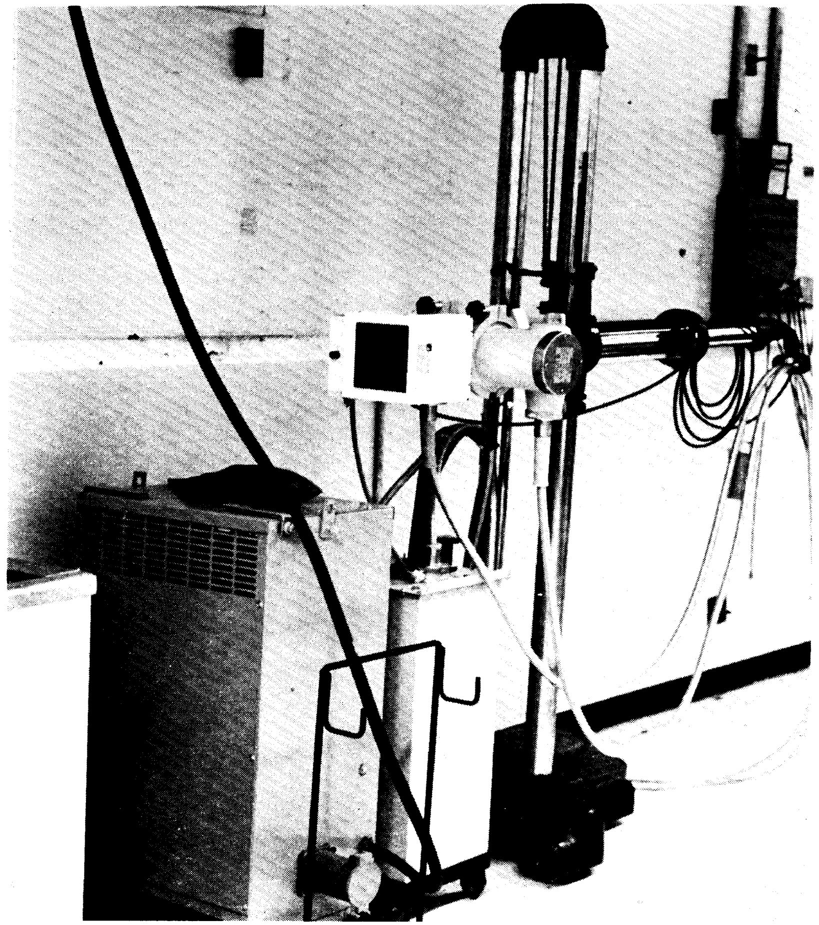
Several important factors that affect the performance of this system are: 1) percent ripple in the x-ray generator beam output, which has an effect on motion-picture film density, and, consequently, on radiographic contrast from frame to frame in a high-speed sequence of 12 ms duration, for example, 2) gating pulse shape, which should be near to a square wave as possible, in order to use the full gain of the image intensifier tube during the few hundred microseconds it conducts information, and to avoid defocussing from variation in photo anode accelerating potential during this time, 3) gating pulse synchronization with camera framing shutter, to receive full output information on each film frame presented to the image tube output phosphor, 4) light output pulse decay time, to assure that the chain

FIGURE 1. Schematic Diagram of Impact Experiment





(a) Detector elements



(b) X-ray generator elements

FIGURE 2. High-Speed Cineradiographic System Components

of four phosphors through the image tube have decayed to nearly zero output, to avoid integration of residual images in a sequence with subsequent loss of contrast, and 5) resolution and distortion of the output image when the system is operated in gated mode, to verify optically that the system is operating at or near its full capability. These factors have been measured, and are discussed below.

Percent ripple is defined here as the ratio of the peak-to-peak sinusoidal amplitude variation to peak d-c amplitude, measured from a d-c zero baseline, times 100. Other definitions of ripple sometimes use root-mean-square values or average values of the a-c component riding on a d-c level, but peak-to-peak measurement is more meaningful in this application because resultant film density is a function of excursions from maxima to minima in energy transfer through the system. Figure 3 shows the ripple on the 125 KvP, 100 mA x-ray output, obtained with a calcium tungstate scintillator directly coupled to the window of an RCA-931A photomultiplier tube, d-c coupled to an oscilloscope. The x-ray generator was operated for 0.1 sec.; the abscissa represents time running toward the left in units of 20 ms/div. Ripple frequency is 120 Hz, with a period of 8 ms, which corresponds to the full-wave rectification frequency. In this case the percent ripple is approximately 7%, which has been found to be quite suitable for high-speed cineradiography at HSRI. The degree of ripple in the x-ray intensity output is directly proportional to x-ray tube current, and inversely proportional to x-ray tube anode potential. In experimental situations encountered, appropriate combinations of voltage and current have yielded useful cineradiographic film sequences.

Gating pulse shape is shown in the upper trace of Figure 4. The peak amplitude of this signal is proportional to a positive 3.3 Kv gate pulse, applied to the input photocathode of the image intensifier tube, which is normally at ground potential when the tube is in a conducting state. The 3.3 Kv gate pulse raises the normally grounded photocathode to approximately the same potential as the first dynode ring in the first stage of the image tube. This produces a nearly zero potential gradient, and therefore no photo-electron flow between input photocathode and the first dynode, shutting the image tube off.

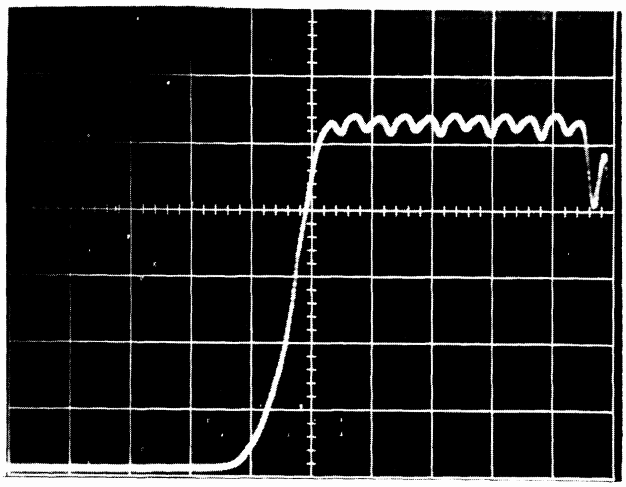


FIGURE 3. 7% ripple on smoothed full-wave rectified x-ray output at 125 KvP, 100 mA; 20 ms/div., time running to left.

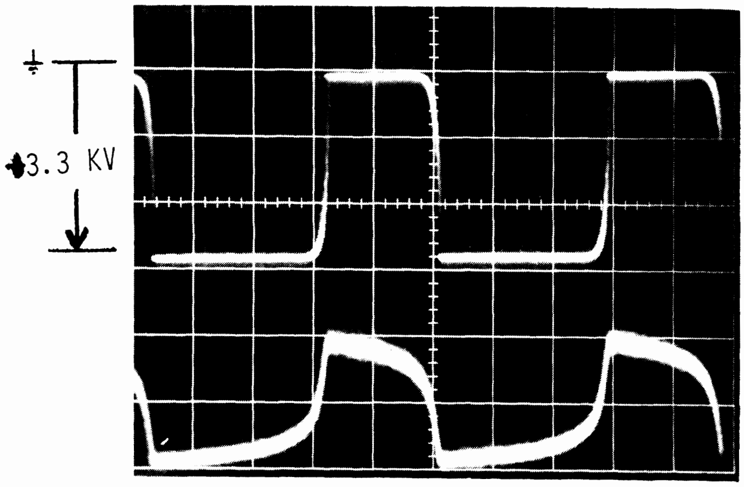


FIGURE 4. Pulse shapes and synchronization of light output with image tube gate pulse.
Upper trace: 3.3 Kv image tube gate pulse, 1 KHz input frequency, gate pulse width control at 0.2 ms/div.
Lower trace: PM tube record of image tube light output, 0.2 ms/div.; time running to left.

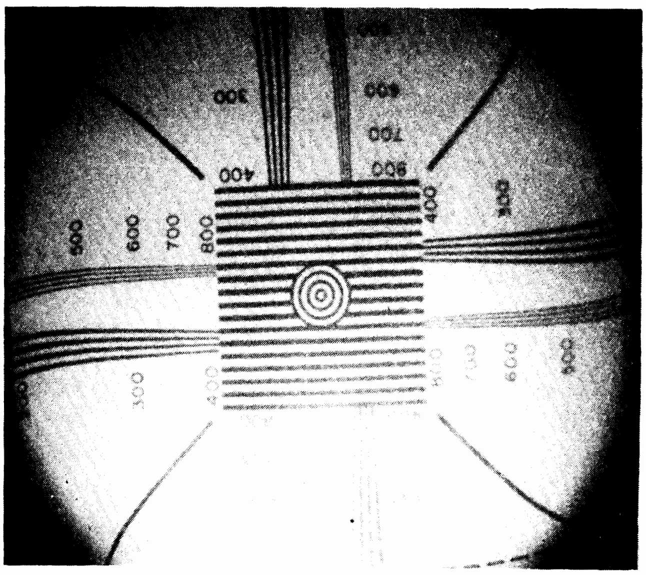


FIGURE 5. Resolution in pulsed mode operation; 35 Kv dc image tube accelerating potential, 1 KHz gate pulse frequency; 293 μs pulse width; optical magnification ratio of 1:6; minimum resolvable dimension: 0.55 mm in object space.

When the gate pulse voltage falls to zero, the photocathode is again in its normal ground state and tube conduction occurs. In this example the tube was on for nearly 400 μs, and off for about 600 μs, at 1 KHz pulse repetition rate. Pulse width is controllable, and is normally set at a width of 225 μs to overlap camera shutter open time of 200 μs at 1000 frames per second. The gate pulse is an excellent approximation to a square wave, with a rise time of approximately 50 μs, without ringing, overshoot, or variation in required voltage level.

Light output decay time is shown in the lower trace, where the abscissa is in units of 0.2 ms/div., time running to the left. The image tube has three fast phosphors with a decay time of 5 μs each, and a P-11 output phosphor with a decay time of nominally 90 μs. Decay time of the chain is the convolution of all of them, but approximately 200 μs is seen on the lower trace; this also includes interdynode capacitance of the image tube and time constant of the photomultiplier measurement circuitry. The dominant contributor to this decay time is the P-11 phosphor, which actually does not have a unique time constant, but varies proportionally according to excitation level and also to time duration of excitation. When the gate pulse width is narrowed to approximately 200 μs, decay time becomes smaller, which allows a higher x-ray input level necessary for relatively dense subjects. The light output in the example shown is seen to fall to nearly zero before the onset of a successive gate pulse.

Optical verification of resolution performance is shown in Figure 5. A video test pattern chart, illuminated by a d-c incandescent light source, was viewed by the image intensifier in gated operation at 1 KHz pulse repetition rate; pulse width was 293 μs; optical magnification ratio was 1:6, i.e., the actual diameter of the test pattern viewed by the image tube objective lens was 12 in, reduced to a 2 in. diameter on the photocathode. The image seen in Figure 5 is a Polaroid photograph of the image tube output phosphor. Density variation is due to specular reflection from the test pattern chart, and also to non-uniform illumination, because the light source was not completely diffuse.

All lines are seen to be clearly resolvable at maximum convergence. The minimum width of a single black line on the actual test chart is 0.5 mm; so the system has capability to easily resolve 0.5 mm in object space. In order to obtain the maximum resolution possible from an x-ray fluorescent screen of typically 5 line pairs/mm (0.2 mm in object space) and the image tube specification of 22 lines pairs/mm, a 16-mm high-speed motion picture camera and film combination of 110 line pairs/mm would be required; this is not attainable with the rotary prism type camera used in this system, or any 16-mm motion picture camera within reasonable cost.

Magnetically focussed image intensifiers display a characteristic spiral, or S-type distortion, which is seen at the edges of the image in figure 5 as displacement from linearity of the image of a line. These tubes provide least distortion and highest edge resolution compared to electrostatically focussed tubes, which give a pincushion type distortion and defocussing at its edges. Error correction for distortion in quantitative measurements is straight-forward, and depends on well-known analytical methods which are generally part of computer programs.

Applications to Biomechanics Research

Current injury assessment research is aimed at four regions of the human body: the head, neck, thorax, and knee. This system has been applied to all of these regions in various experimental programs at HSRI. Each subject specimen presents a different problem in choosing x-ray factors, targeting, and geometry so that optimum density and contrast will be obtained in the film. Targeting structures of interest involves selection and placement of radiopaque materials to provide contrast enhancement.

An example of an application of this system to head impact response is shown in Figure 6, which shows a 1000 frame per second sequence reproduced from 16-mm motion picture frames. This example is presented because high-speed cineradiography of the head offers a good test of system capability. The human head comprises a dense highly x-ray absorbing and scattering material; moreover, targeting of this material is a difficult problem in an impact situation.

Targets consisting of 0.25 in. lead pellets are seen in Figure 6 distributed throughout the brain tissue and skull bone. A two inch horizontal reference scale is seen at the center of each frame, together with a vertical reference line running from top to bottom of each frame. The characteristic S-type distortion is also observed in the vertical reference. Impact occurred from left to right from a pneumatically driven testing machine specifically constructed at HSRI for impact studies. Peak force was of the order of 8 kiloNewtons, 10 ms duration, with a peak resultant linear velocity of 7 m/sec. The sequence shown in Figure 6 covers a period of 12 ms; frames are 1 ms apart.

The purpose of the head impact experiment was to study application of three-dimensional motion analysis using accelerometry, brain vascular system pressurization, and high-speed cineradiography to understand more about head injury mechanics. Analysis of the head acceleration data indicated existence of brain motion relative to the motion of the skull, and this was confirmed by high-speed cineradiography. Details and discussion of experimental methods and results are given in the paper entitled, "Head Impact Response" (Stalnaker, et al.), which is listed in List of Publications based all or in part on this NSF-supported project accompanying this report. The quality of the high-speed cineradiographic output is of principal interest in this discussion, as follows.

Ripple encountered at voltages and currents most often used are not a significant problem. Densities from frame to frame are quite uniform. The principal effect of ripple is seen in the central lower region of the brain where x-ray attenuation is the greatest. Frames 5, 6, and 7 show this effect of a slight falling off of x-ray kilovoltage, current, and therefore, x-ray intensity. Brain material x-ray absorption and scattering cross-sections vary as a function of x-ray energy, generally increasing in absorption for lower energies; scattering worsens for higher energies, but as the film sequence densities show, all features of interest are clearly discernable for the degree of ripple present.

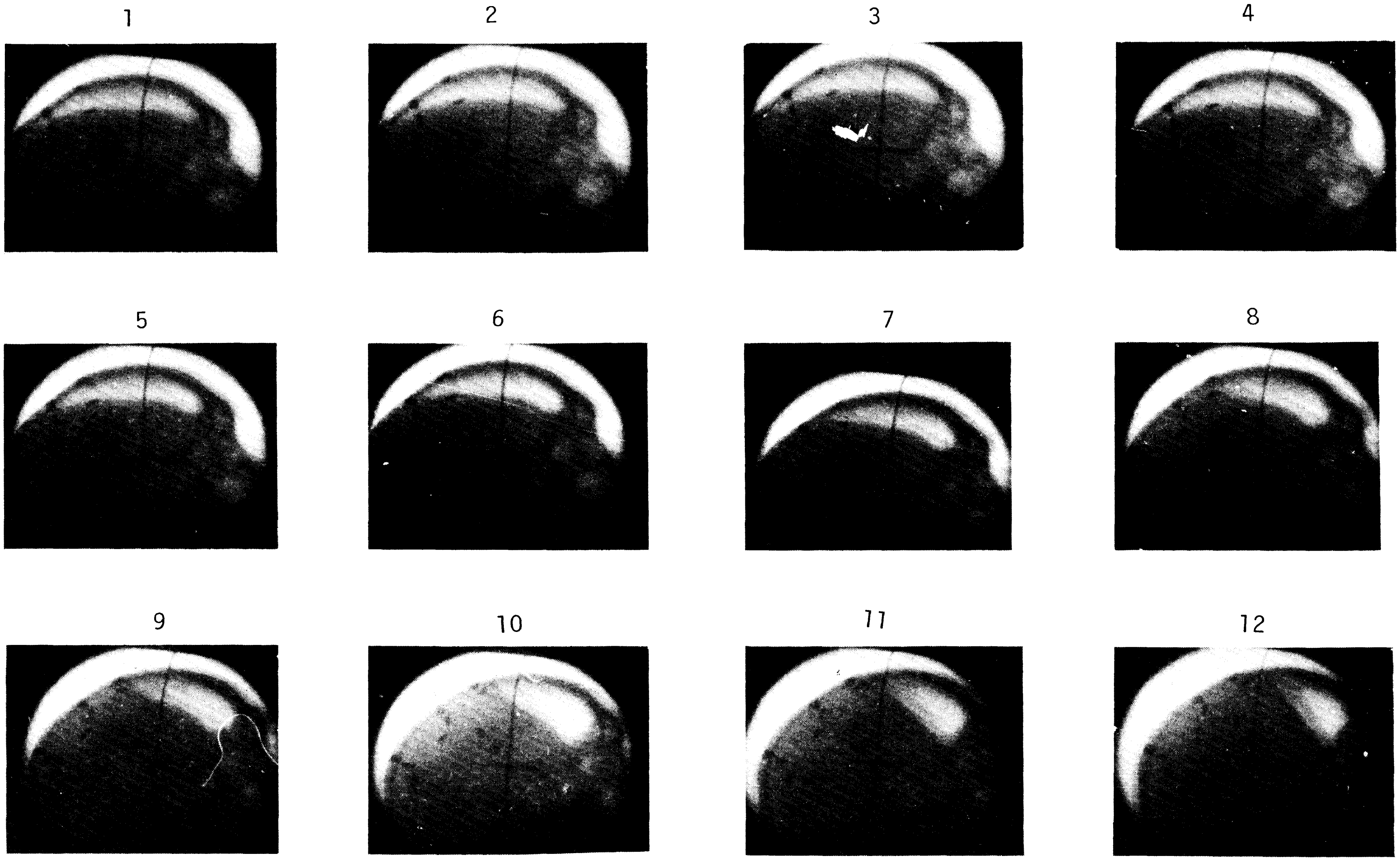


FIGURE 6. Example of 1000 frame per second, 16-mm cineradiography in head impact sequence; impact occurred from left toward right.

Contrast between skull bone and train tissue is observable, and contrast enhancement between targeted points and biological material is clearly seen. Image resolution appears to be maintained from frame to frame. The anatomy of frontal bone structure is also clearly discernable, which assists in location of the separation between bone and brain tissue as brain motion progresses.

In conclusion, the high-speed x-ray cineradiographic system developed at HSRI is regarded as a successful development with potential for significant contributions to biomechanics research, particularly so when needed optical improvement factors are accomplished, and the system moves into three-dimensional x-ray stereophotogrammetry for biodynamic response model validation.

List of publications based all or in part on this NSF-supported project:

1. M. Bender, W. L. Rogers, and J. W. Melvin, "HSRI High-Speed X-Ray Cinematographic System for Biomechanics Research," Effective Utilization of Photographic and Optical Technology to the Problems of Automotive Safety, Emissions, and Fuel Economy, Society of Photo-optical Instrumentation Engineers, Palos Verdes, CA., 1975.

2. M. Bender, J. W. Melvin, and R. L. Stalnaker, "A High-Speed Cineradiographic Technique for Biomechanical Impact," Proceedings of Twentieth Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA., 1976.

3. R. L. Stalnaker, J. W. Melvin, G. S. Nusholtz, N. M. Alem, and J. B. Benson, "Head Impact Response," Proceedings of Twenty-first Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA, 1977.

4. R. L. Stalnaker, M. Bender, and J. W. Melvin, "Safety Helmet-Head Interaction Study Using High-Speed Cineradiography," Final Report UM-HSRI-77-48 to National Institutes of Occupational Safety and Health, Morgantown, W.V., 1977.

5. R. H. Culver, M. Bender, R. L. Stalnaker, and J. W. Melvin, "Evaluation of Intrathoracic Response Using High-Speed Cineradiography," to be presented at the Sixth Annual New England Bioengineering Conference, Univ. of Rhode Island, Kingston, R. I., March 23-25, 1978.

6. M. Bender, J. W. Melvin, R. L. Stalnaker, and W. L. Rogers, "A High-Speed Cineradiographic Technique for Biomechanics Research," to be presented at the 13th International Congress on High-Speed Photography and Photonics, Tokyo, Japan, August 20-25, 1978.