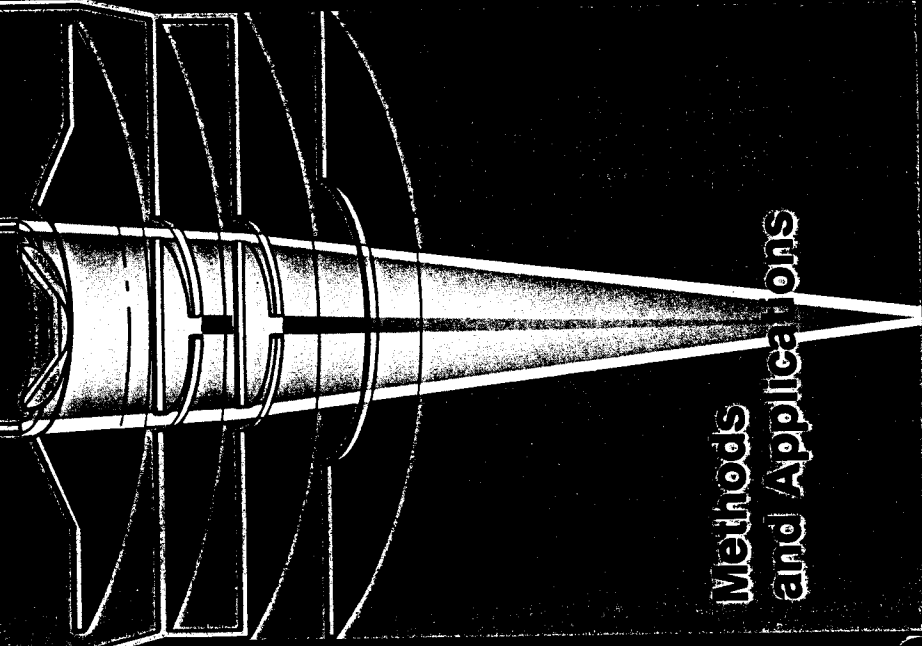


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PULSED X-RAY TUBES...



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Practical Applications of Pulsed X-Ray Tubes

It is now over eighty years since the discovery of X-rays by Wilhelm Roentgen. In that time, the physics of X-rays has been well explored, leaving little, if any, basic research to be done. Applied research in the practical application of X-rays is, however, still far from exhausted. One need only attend the Annual Denver X-Ray Conference to sample the current variety of X-ray research. In the fields of science, industry and medicine, X-rays remain an indispensable means of probing matter.

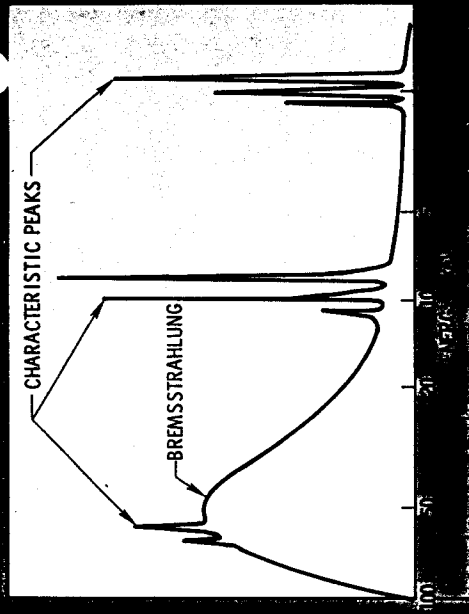
Since X-rays are light waves of very short wavelength (10–0.1 Å) they can reveal details down to atomic dimensions, while their high energy allows them to penetrate most otherwise opaque objects non-destructively. X-ray photons are commonly generated by one of two means: either the decay of radioactive isotopes or the scattering of electrons by atoms. Radioisotopes produce X-rays primarily by electron capture. The X-radiation is monoenergetic and of relatively low intensity. The X-ray fluorescence applications of radioisotopes are confined to a limited number having both useful half-lives and applicable emission energies. The main attraction of isotope sources are simplicity, stability and the lack of power supply requirements. The second means of creating X-rays, electron scattering, operates by two fundamentally different processes. When electrons are scattered by the atomic nucleus the resulting photons form a continuous energy spectrum with a maximum energy equal to the maximum incident electron energy and a broad intensity peak at about two-thirds the maximum energy. This radiation is called bremsstrahlung (radiation by deceleration). Sufficiently energetic electrons can collide with inner shell atomic electrons freeing them from their bond state. When an electron from another shell fills the

vacancy created, a photon equal to the energy difference between states is given off. Each element has a distinct collection of photon energy known as characteristic radiation. The peak characteristic intensities are typically many times greater than the associated bremsstrahlung radiation, as shown in Figure 1. Electron generated X-rays are easily controlled and require none of the handling precautions associated with radioisotopes. The ability to manipulate X-ray intensity (by varying the electron beam current) and energy (through electron accelerating voltage) over a wide range results in a flexibility not possible with radioisotope sources. This flexibility is a major reason why X-ray tubes remain the most common source of X-rays in laboratory and industrial use.

Despite the fact that modern X-ray tubes are basically the same as the 1913 Coolidge tube, important refinements continue to be made. Some recent advances have been the transmission target X-ray tube, the miniature X-ray tube and the multi-grid X-ray tube. Part of the research at Watkins-Johnson has been spent examining various means of pulsing X-ray tubes. This research was motivated by the practical applications which exist in X-ray spectrometry, industrial quality control, and medicine. Particular attention was paid to the possibility of pulsing existing X-ray tubes with their present power supplies (e.g. systems currently in use by X-ray spectroscopists).

X-Ray Analysis

The two approaches to material analysis using X-rays are wavelength-dispersive and energy-dispersive analysis. In wavelength-dispersive analysis the sample fluorescence is dispersed by diffraction from a single crystal. An intensity sensitive detector is swept through an angular range and the wavelengths determined from Bragg's law. In



energy-dispersive analysis the sample fluorescence is incident on an energy sensitive detector and the dispersion is accomplished electronically. The growth of energy-dispersive X-ray analysis has proceeded rapidly since the development of the solid-state detector. These new detectors are fast and capable of good energy resolution. The primary advantage of energy-dispersive analysis as compared to wavelength-dispersive analysis is a more rapid analysis, in general, for both qualitative and quantitative measurements. This article will consider energy-dispersive analysis only. Although, in principle, wavelength-dispersive systems can be pulsed, most

X-ray tubes currently used in such systems cannot.

A typical energy-dispersive analysis system employing the direct X-ray excitation of a specimen is shown in Figure 2. X-rays generated by the tube are used to stimulate secondary emission from a specimen and the resulting fluorescence is intercepted by a lithium-drifted silicon detector. The detector and an integral FET preamplifier, cooled by liquid nitrogen, produce voltage steps from the electron-hole pairs created in the detector by the incident X-ray photons. These voltage steps are proportional in height to the energies of the inci-

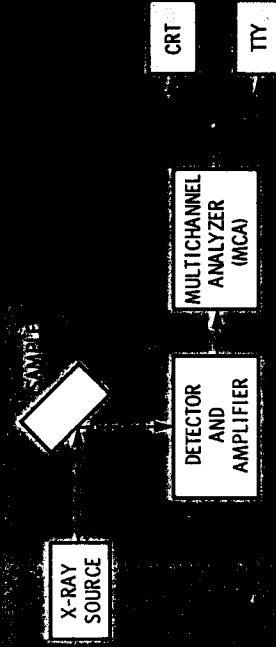


FIGURE 2

dent photons. The output from the preamplifier is then fed into a linear amplifier and pulse shaper before entering a multi-channel analyzer (MCA). Data from the MCA can then be output to a number of peripherals, such as a CRT display or a teletype, for analysis. The separation between tube, secondary target and detector is usually quite small and the X-ray path is often in a vacuum.

The high X-ray intensity which results at the detector is responsible for the relatively short acquisition time, but the acquisition time cannot be shortened without limit. As the intensity at the detector is increased, a point is reached where no further reduction in acquisition time results and beyond which acquisition time begins to increase. This condition is a result of the inability of the signal processing electronics to keep pace with the detector output.

The minimum recovery time for a modern solid-state detector is about 200 nanoseconds. This is equivalent to 5×10^6 cps (counts per second), maximum, with no energy resolution. At an energy resolution of 160 electron volts, a maximum count rate of 2×10^4 cps would be typical. Greater energy resolution requires a longer shaped pulse from the linear amplifier, thus reducing the maximum acceptable count rate.

When the incident intensity is so great that pulses from the linear amplifier occasionally overlap, the linearity between pulse height and photon energy begins to break down. In order to maintain linearity and energy resolution, the amplifier incorporates a pulse pile-up rejection circuit. This circuit prevents overlapping pulses from reaching the MCA. When pulses are detected too close together, relative to the shaped-pulse width, the overlapping pulses are rejected by blocking their input to the MCA. This time period, during which the elec-

tronics is busy processing a pulse and cannot process another pulse, is known as dead-time. Dead-time can also result when a pulse enters the MCA before the analog-to-digital (A/D) conversion of the previous pulse is complete. On the other hand, time spent waiting for pulses and performing analysis is known as live-time. Both live- and dead-time are responsible for increasing the acquisition time.

Another phenomenon results when pulses are so close together that they cannot be distinguished by the electronics as piled-up pulses. Such pulses are processed as a single pulse whose amplitude is equal to the sum of the individual pulses. These pulses yield the "sum peaks" (false counts at twice the energy of the most intense photons) often visible in the pulse height analysis (PHA) output, when high count rates are maintained.

Improved System Performance with Pulsed Tubes

One procedure for minimizing the acquisition time is to control the X-ray source intensity. As the intensity at the detector increases, so does the probability of pulse pile-up. The chances of pulse pile-up can be reduced by using the gridded X-ray tube, as shown in Figure 3. This tube can be turned off and on with a low voltage signal. The linear amplifier in the detection system of Figure 4 normally supplies two signals: one from the "fast discriminator" which acknowledges the input of a pulse from the detector and contains only temporal information, and a second signal from the "slow discriminator" which is a shaped pulse containing information on the incident photon energy. The linear amplifier in Figure 4 contains the slow discriminator. A third signal from the MCA, usually labeled "ADC busy" indicates whether a shaped pulse is undergoing A/D conversion. If the X-ray tube is turned off by the fast discriminator signal when a detected

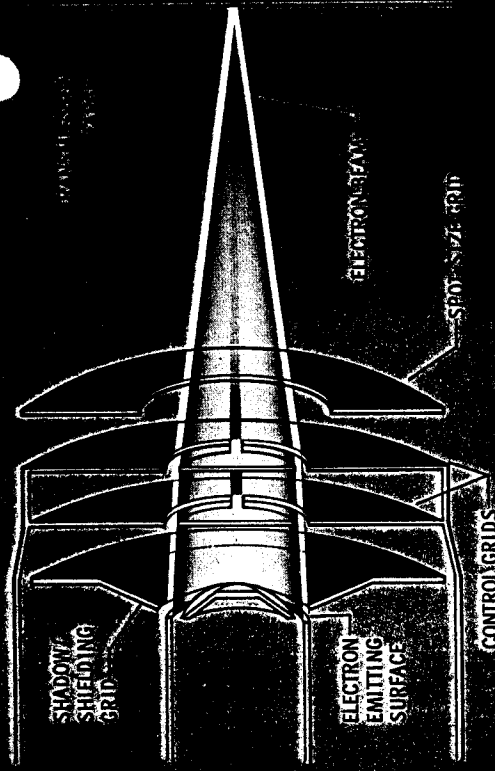


Figure 3. A cross-sectional view of a gridded X-ray tube.

pulse enters the linear amplifier and is turned back on by the signal from the ADC busy line when the MCA is finished processing the pulse, then the only pile-up which can occur is due to coincident pulses, and a reduction in acquisition time is obtained. Further refinements in this direction result in less significant reductions in acquisition time. A typical pulsed energy dispersive system is shown in Figure 5. Two groups, J. Jaklevic, et. al. (2) and A. Sandborg, et. al. (3), have reported considerable reductions in analysis

time using such techniques. Figure 6A shows data taken at the Watkins-Johnson laboratories using a system similar to that of Jaklevic, et. al. At 28,000 counts per second input, nearly twice as many counts are processed by the MCA using a pulsed tube as compared with continuous operation. Figure 6B shows similar data versus average anode current.

Narrow Width Pulse Generation

Most energy-dispersive analysis sys-

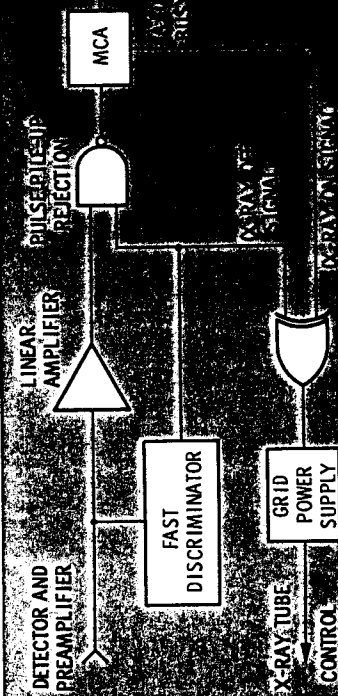


Figure 4. Logic of basic pulsed-tube controlled circuit for spectroscopy system.

and the transmission line discharges across the load, sending a voltage step down the line. When the output impedance is carefully matched to the transmission line, the voltage pulse height is about $V+2$. The pulse width is determined by the length of transmission line. Since the pulse height can be increased by stacking several transistors in series, the maximum pulse height depends on the transistor breakdown voltage. A four-transistor stack using 2N2222 transistors produced a 170 volt pulse for a supply voltage of 530 volts. Pulse widths between 1 microsecond and 200 nanoseconds with a 20-nanosecond rise time and a 50-nanosecond fall time were achieved by varying the transmission line length. These measurements were performed on a 50 kilovolt, 1 milliamper X-ray tube that is commonly used in current spectrometry systems. Further reductions in rise and fall times can be achieved by designing tubes requiring less grid voltage.

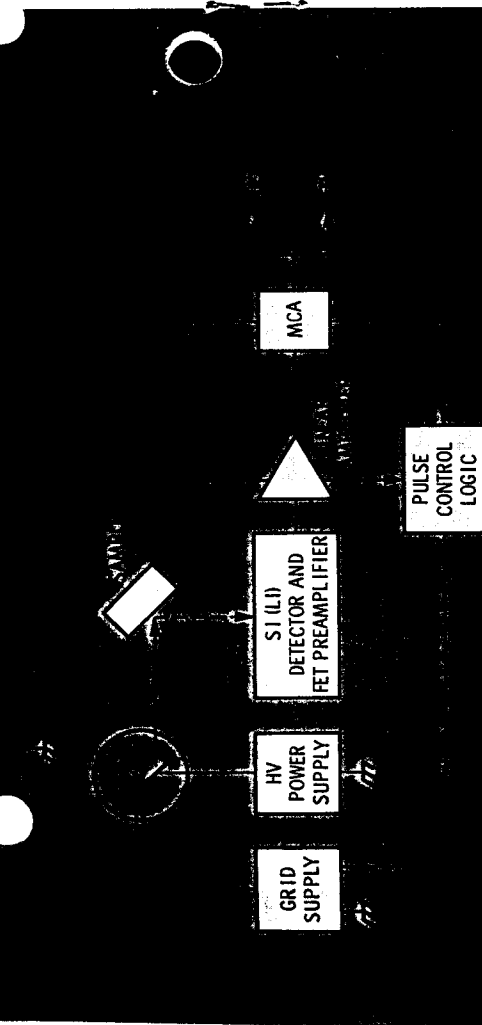
Designing a Pulsed X-Ray Tube

Pulse shape is ultimately constrained by the X-ray tube characteristics, such as grid-cathode capacitance, mutual transconductance, etc., and the time constants of its power supplies. In

a fast rise and fall time (tens of nanoseconds) is desirable. The previously discussed pulsed system is limited in its ability to produce fast pulses due to its interconnection to the power supply control circuits. We examined two methods of generating short X-ray pulses. In both instances a gridded X-ray tube was switched on and off as shown in Figure 7. In the first case an Electron Bombarded Semiconductor (EBS) switch (4) was used to drive the control grid of a conventional X-ray tube.

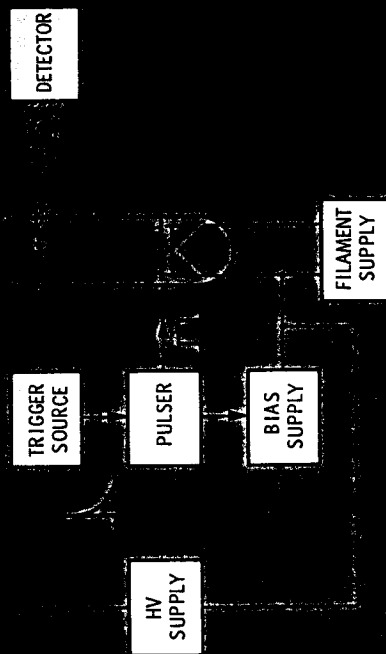
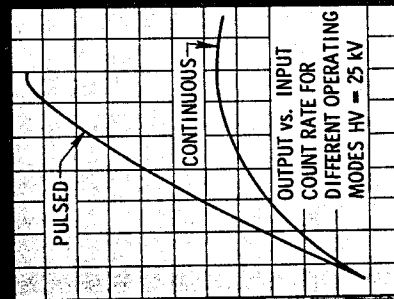
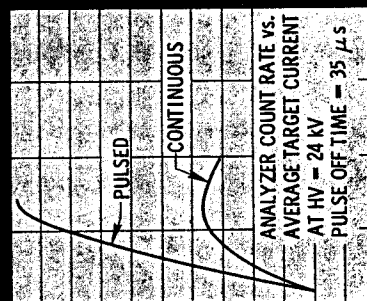
An EBS Switch is essentially a p-n junction stimulated by an electron beam and is typically capable of switching about 40 volts per nanosecond across a 2.5K ohm load. We were able to achieve a 100-400 nanosecond fall time at a peak anode current of approximately 1.0 milliampere using a standard 50 kilovolt gridded X-ray tube.

Another approach was to use an avalanche transistor switch as shown in Figure 8. This rather simple pulse generator operates as follows: In the absence of an input trigger, the open-ended transmission line charges to a voltage of approximately $V+$. The input trigger turns on the transistor



tion these tubes can be driven to somewhat higher peak anode currents before their maximum power dissipation is reached. Thus, a higher X-ray intensity is achieved during the pulse. As a consequence, the first detected pulse comes sooner after the tube is turned on, thereby reducing the live-time. Under these conditions a short duration pulse (>1 microsecond) with

tems in use today employ X-ray tubes with one or more grids to control anode current. In this manner, sensitive feedback circuits maintain the X-ray output constant to within a few tenths percent over several hours. Such tubes are usually suitable for pulsed operation, and several manufacturers of X-ray spectrometry systems now offer a pulsed tube option. In pulsed opera-



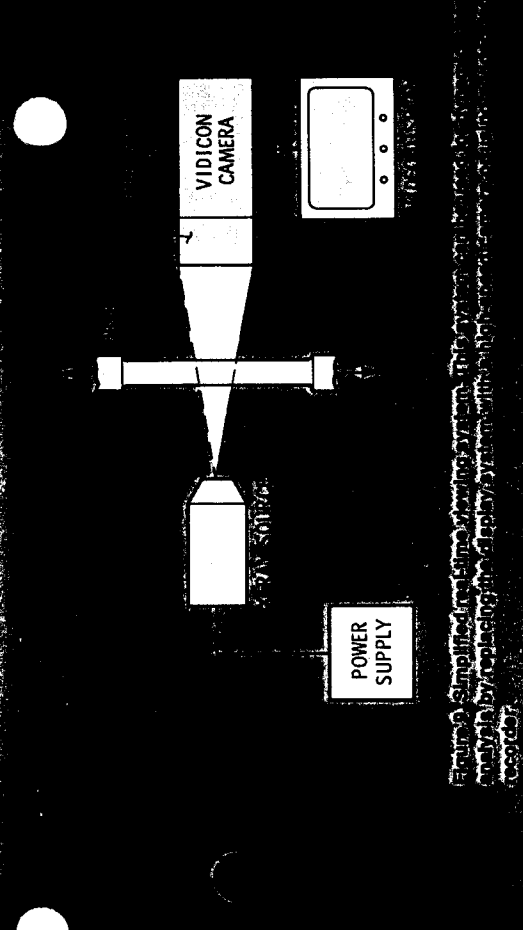


Figure 9. Simplified time-sharing system. This system can be analyzed by replacing the display system with a video recorder.

order to reach greater anode currents with less grid voltage, a tube with a larger mutual conductance was designed. A prototype tube was constructed and yielded about 80 mA peak anode current for a peak grid voltage of 90 volts. The pulse width was 5 microseconds and the pulse period was 1 millisecond. This yielded an average anode current well within the power capabilities of the tube. Transistor switching is adequate for this application as long as the current demand is not too great. Also, when increasing the mutual conductance, the interelectrode capacitance must not be allowed to get too large. The best results are obtained by systematically adjusting the tube parameters until the optimum pulse shape is achieved within the constraints of the pulsing circuitry.

Other Applications of Pulsed X-Ray Tubes

Pulsed X-ray sources have many potential applications outside the field of spectrometry. One example is a real-time viewing system. In such a system, an object to be viewed is placed between an X-ray source and the image intensifier screen (see Figure 9). An image transfer device (e.g. a vidicon camera and video display) is normally employed to present the object

to the operator. Since the object image will ultimately be integrated by the eye, which cannot detect pulses faster than a few tens of cycles per second, there is no need for a faster renewal of the monitor image. Thus the source need only be pulsed on enough to yield sufficient activation of the intensifier screen. This condition allows a higher peak pulse power and increased intensity at the intensifier screen. Some situations require pulses even less frequently, reducing the duty factor further and allowing still greater peak intensities.

Pulsing the source also has the added benefit of extended tube life over continuous operation. Pulsed systems can be of valuable assistance in the examination of discrete products on a moving belt or the periodic monitoring of a continuous product. The source is active only when objects are present and the object motion is "frozen" allowing a clear image for analysis.

The examination of packaged foods for "tramp" materials (undesired foreign objects) and content distribution can be performed as shown in Figure 10. This system can be fully automated by allowing a computer to examine the X-ray images and direct the removal of those products not meeting

certain specifications. The pulse width, X-ray energy and intensity can be chosen so that good image resolution results. Soft (low energy) X-rays are usually adequate to differentiate between food products and denser foreign materials such as glass and metal. Vidicon type tubes with thin beryllium windows are commercially available which respond directly to soft X-rays thus improving the resolution and signal-to-noise ratio.

The on-line examination of cable core concentricity is an example of monitoring a continuous process. Pulsing two tubes, whose axes are per-

pendicular to each other and the cable core, yields periodic information on the core position along the cable length. This information is continually fed back into the manufacturing processes through a microprocessor based system which instantaneously corrects for position deviations outside tolerance limits. A similar approach can be taken with thickness gauging of paper and metal sheet. Composition (i.e. material analysis) measurements can be performed simultaneously with thickness or position determinations.

Cine-radiography systems are similar to real-time viewing systems except that the vidicon tube is replaced by a

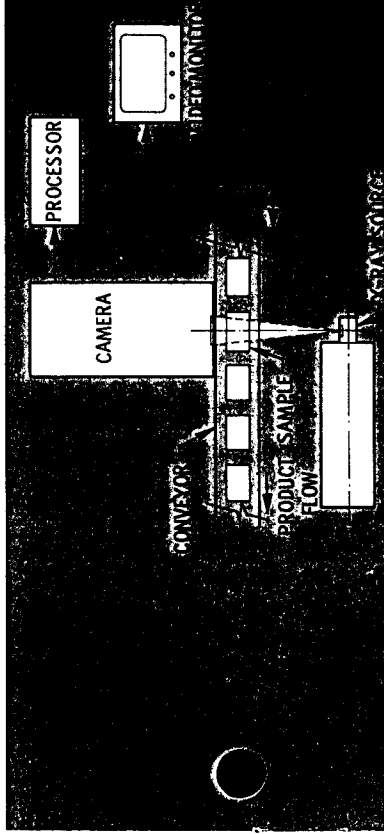


Figure 10. A typical camera setup at a food conveyor with process control.

high-speed camera. Current cine-radiography systems use either a pulsed field emission X-ray tube or a continuous source and a gated high-gain image intensifier with high speed camera (1). The advantages of pulsing a gridded X-ray tube as compared to a field emission tube are inherently longer tube life and variable X-ray intensity at fixed anode voltage. When compared to continuous operation, pulsed operation offers greater intensity for the same average power dissipation, since the tube need only be on during the exposure periods. Pulse rise times on the order of tens of nanoseconds are competitive with 10 microsecond exposure times and framing rates of 10,000 per second available with gold intensifier tubes. There are a number of applications in the study of transient phenomena, such as dynamic stress analysis, explosion and implosion phenomena, where pulsed cine-radiography systems could be applied.

Pulsed X-ray sources have also been used in communications. In a simple communications scheme involving two logic states (on or off, one or zero), the pulse width and rise time determine the speed of information transmission. A transmission rate of about 2.5M BPS (bits per second) is conceivable with current tube technology. This is about equal to the detection limit estimated from the detector response of the fastest solid-state detectors presently available.

In medicine, accurately timed radiation exposures are possible without the use of mechanical shutters. There are also medical applications for in-

vivo (e.g. X-ray fluorescence thyroid scan) and in-vitro (e.g. elemental analysis of blood and tissue samples) energy-dispersive analysis. Pulsed operation of the new brain and body scanners (computerized axial tomography systems) is highly desirable but will require some advances in high power X-ray tubes.

Summary

X-ray tubes have traditionally been operated in a continuous mode. The advent of multi-grid X-ray tubes has allowed pulsed operation at peak intensities beyond the continuous ratings. The continuous operation of many systems means an unnecessary use of energy and shorter tube life, in general, when compared to pulsed operations. The first point is particularly important where portable X-ray systems are employed. Pulsed mode operation is a valuable technique that has not yet been fully utilized. However, its use in energy-dispersive spectroscopy systems has become commonplace and its use in industrial quality control is growing steadily. Greater acceptance will open up more applications. The effort at Watkins-Johnson Company has been aimed at expanding the range of pulse widths to shorter times along with faster rise and fall times. We have also considered the influence of tube construction on pulse parameters with the hope that a greater range of applicability will accompany increased operational flexibility. It is not believed that the limits imposed by current technology have been reached. A continuing effort in this direction is needed.

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