AAPM REPORT NO. 14

PERFORMANCE SPECIFICATIONS AND ACCEPTANCE TESTING FOR X-RAY GENERATORS AND AUTOMATIC EXPOSURE CONTROL DEVICES

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Report of the
Diagnostic X-Ray Imaging Committee
Task Group on Performance Specifications
and Acceptance Testing for X-Ray Generators
and Automatic Exposure Control Devices

Raymond P. Rossi (Chairman)
University of Colorado Health Sciences Center
Denver, Colorado 80262

Pei-Jan Paul Lin
Northwestern University Medical School
Chicago, Illinois 60611

Phillip L. Rauch
Henry Ford Hospital
Detroit, Michigan 48202

Keith J. Strauss
The Childrens Hospital
Boston, Massachusetts 02115

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Raymond P. Rossi
University of Colorado Health Sciences Center
Denver, Colorado 80262

Pei-Jan Paul Lin
Northwestern University Medicalchool
Chicago, Illinois 60611

Phillip L. Roach
Henry Ford Hospital
Detroit, Michigan 48202

Keith J. Strauss
The Children8 Hospital
Boston, Massachusetts 02115

INTRODUCTION

This report is the result of a charge from the Diagnostic X-Ray Imaging Committee of the American Association of Physicists in Medicine to develop a document addressing performance specifications and acceptance testing methods for x-ray generators and automatic exposure control devices. To execute this charge a task group was formed in November of 1981. This report reflects the collective efforts of the task group to provide a document which would be useful to practicing medical physicists who might be called upon to assist in the development of bid documents and the evaluation of performance specifications and acceptance testing of these components of radiological imaging systems.

This report is divided into three parts relating to x-ray generators and automatic exposure control devices. The first part contains background information concerning the principles of operation of x-ray generators and automatic exposure control devices. The second part identifies relevant characteristics of x-ray generators and automatic exposure control devices for which performance specifications would be useful vendor to assist in evaluating different types of equipment. The third part outlines details of test methods for evaluating clinically installed equipment for purposes of acceptance testing and levels of performance which might be reasonably anticipated.

This report is not presented as definitive but rather as guidance to be used by professional medical physicists as they see fit. It is anticipated that revisions will be needed as technological advances in the areas of x-ray generators and automatic exposure control devices are made.

PART 1

PRINCIPLES AND CHARACTERISTICS OF DIAGNOSTIC XRAY GENERATORS AND AUTOMATIC EXPOSURE CONTROL DEVICES

This section of the report contains background information concerning the basic principles and characteristics of x-ray generators and automatic exposure control devices used in radiological imaging systems. This material is provided to assist the reader in gaining an insight into the function of these components in an imaging system.

X-RAY GENERATORS

Diagnostic x-ray generators are designed to provide electrical energy to be converted into X radiation. The quality and quantity of X radiation is pre-determined by the radiographer who sets the appropriate exposure factors at the control desk. There are many varieties of x-ray generators, and these can be classified according to their source of primary power (Table I) and appearance of the secondary voltage waveform (Table II).

The voltage applied to the x-ray tube can be observed during the exposure by inserting a calibrated voltage divider into the high tension secondary circuit, and displaying the waveform on a dual-trace storage oscilloscope.[1] The single-phase, half-wave rectified waveform [Figure 1 (a)] appears as individual voltage pulses varying from 0 volts to a peak potential, and returning to 0 volts. The voltage ripple is thus 100%. These pulses appear every 1/60th second (16.67 msec), which is one cycle of the mains supply voltage.

The single-phase, full-wave rectified waveform [Fiure l(b)] is similar, with 100% ripple, except that 2 pulses appear per 1/60th second. These two voltage waveforms are inefficient for x-ray production, since both the quality and quantity of X radiation is greatly reduced as the voltage decreases below the peak value. In addition, the half-wave rectified waveform produces useful radiation for less than half of the exposure interval.

A single-phase power supply can be made to produce x-radiation more efficiently by placing a capacitor in parallel with the x-ray tube. Once charged, the capacitor tends to maintain the voltage during the interval when the power supply drops to 0 volts [Figure 2 (a)]. The voltage ripple is thus reduced, and the quality and quantity of X radiation is greatly increased. Note, however,, that the removal of primary voltage, at termination of the exposure, results in a slow discharge of the capacitor which may contribute unnecessary patient exposure. This unnesseary exposure can be reduced by using a lead shutter to block radiation produced after the exposure is terminated. The lower trace in Figure 2 (a) is the radiation waveform, showing that radiation output is blocked by the lead shutter long before the capacitor is fully discharged.

A conventional A.C. line of relatively low power can be utilized to charge a capacitor to rather high potential (e.g., 100 kV). The voltage on the capacitor can then be applied to an x-ray tube to produce x-radiation. For a very short exposure of relatively low mAs, this method produces excellent results. However, for longer exposure both the quality and quantity of X-radiation is severly reduced, as the capacitor is

TABLE I

Sources of Primary Power for the X-ray Generator

Battery
Conventional A.C. line
Dedicated 1 Φ line
Dedicated 3 Φ line

TABLE II

X-ray Generator Secondary Voltage Waveforms

1 Φ (half-wave rectification)
1 Φ (full-wave rectification)
1 Φ Capacitor Smoothed
Condensor Discharge
3 Φ (6-pulse)
3 Φ (12-pulse)
500-1000 Hertz (inverter driven)
Constant Potential

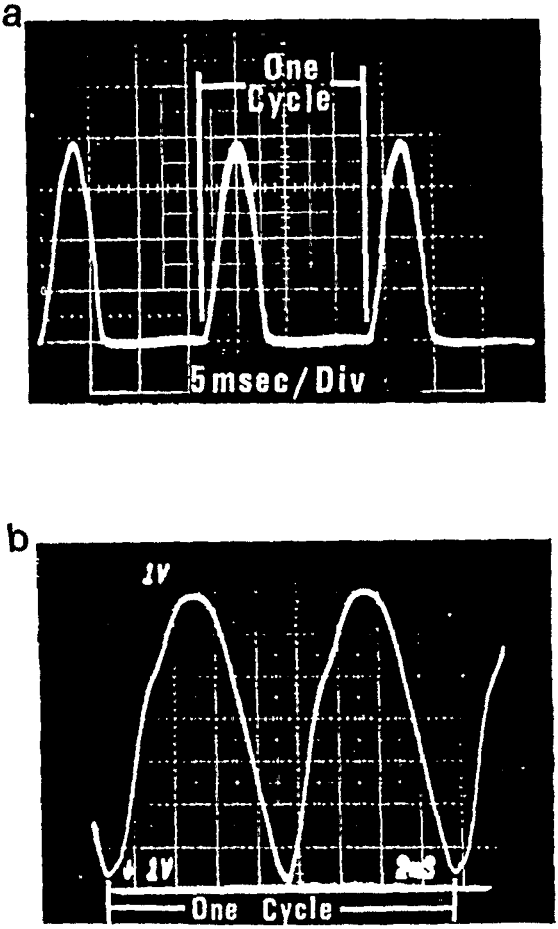
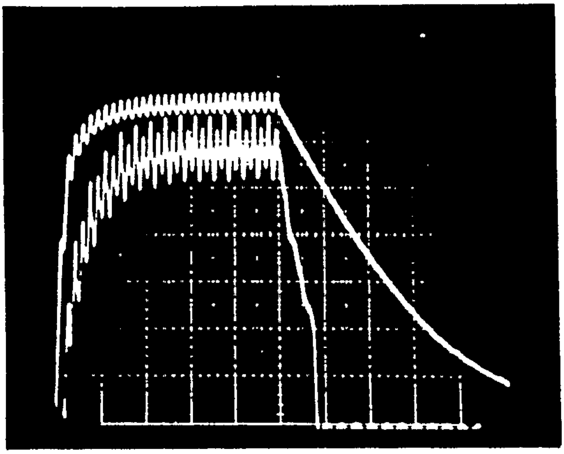


Figure 1. Typical single-phase waveforms: (a) half-wave rectified waveform displayed with horizontal sweep of 5 msec/div., (b) full-wave rectified waveform displayed at 2 msec/div. Note that waveform (a) has Only one pulse and (b) two pulses per cycle of line voltage(16.67 msec.).

a



b

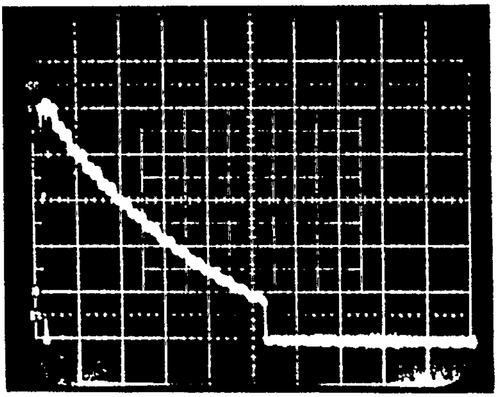


Figure 2. A capacitor can be used to reduce single-phase ripple (a) or as the source of the potential applied to the x-ray tube (b). Figure 2(a) are waveforms from a single-phase capacitor smoothed generator. Upper trace: kV waveform at a vertical sensitivity of 5 kV/div., horizontal sensitivity of 50 msec/div. Lower trace: Radiation waveform. Note that. the condenser slowly discharges following removal of the primary voltage but that the radiation output is quickly blocked by a mechanical shutter. Figure 2(b) is a typical capacitor dischare waveform. For a 1 uf capacitor, the voltage will drop 1 kV Per mAs.

discharged [Figure 2 (b)]. Typically, the voltage on the capacitor drop6 at a rate of 1 kV for each mAs discharge through the x-ray tube. For this reason patient entrance exposure will increase as the selected mAs is increased, whereas the exposure to the image receptor will increase very little.[2]

A dedicated three-phase line can be utilized to produce a relatively low ripple voltage, whose peak value remains constant throughout the exposure. Shown in Figure 3(a) is a 6-pulse waveform, with 6 voltage peaks per one cycle (16.67 msec). Voltage ripple can be further reduced by utilizing a transformer designed to produce 12 pulses per cycle [Figure 3(b)]. Even higher frequency pulses (1,000 Hertz-2,000 Hertz) are available on some mobile and fixed radiographic equipment, which utilizes a battery or conventional power line and rectifiers as the primary power source, and a high frequency invertor to convert the direct voltage to alternating potential.

The ideal voltage waveform is that having 0 ripple or “constant potential” (Figure 4). This can be effectively achieved by means of triode or tetrode control valves p3 placed in the high tension secondary and will be discussed later. There is virtually no increase in radiation quality nor quantity with this waveform as compared with that produced by a 3-phase, 12-pulse generator. The advantage of this configuration lies in the ability of the triode to rapidly switch the high tension as necessary for high speed cineradiographic applications.

Besides the primary power source and the secondary voltage waveform, generators are also classified according to the tube current waveform produced and the type of exposure contacting utilized. The tube current may be applied as a constant load, a falling load (which may actually be a stepped constant load, or a continuously falling load), or a pulsed load. Exposure contacting may be mechanical or solid state.

Each of these types of generators, while significantly different in design, has two major factors in common: (1) each supplies power to an x-ray tube via a transformation of the primary voltage and current, and (2) each requires periodic calibration adjustment. The radiological equipment specialist will often be responsible for maintaining generator calibration, or at least overseeing vendor supplied calibvration. The radiological physicist may be involved in the performance specification and acceptance testing of the x-ray generator as well as periodic cailbration checks. It is therefore imperative that they develop an understading of the requirements imposed on the generator by the x-ray tube and be able to recognize characteristic deficiencies in the generator calibration. They must also realize that no generator is perfect, and some deviation from the nominal technique

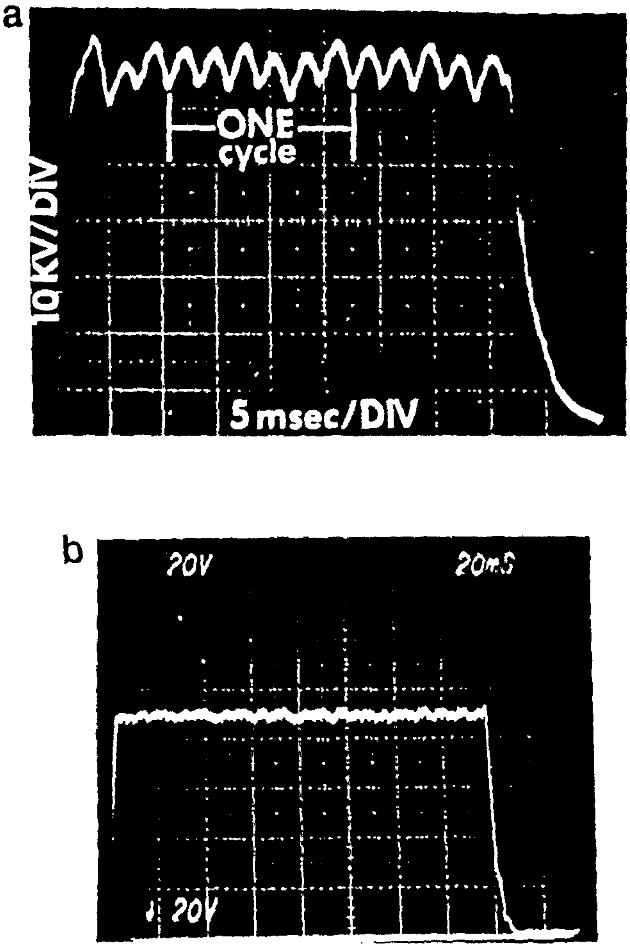


Figure 3. kV waveforms from a dedicated three-phase power line. (a) three-phase, 6-pulse, (b) three-phase, 12-pulse. Figure 3(a) is a 70 kVp waveform displayed at 10 kV/div.(vertical) and 5 msec/div.(horizontial). Figure 3(b) is a 90 kVp waveform displayed at 20 kV/div.(vertical) and 20 msec/div.(horizontial),

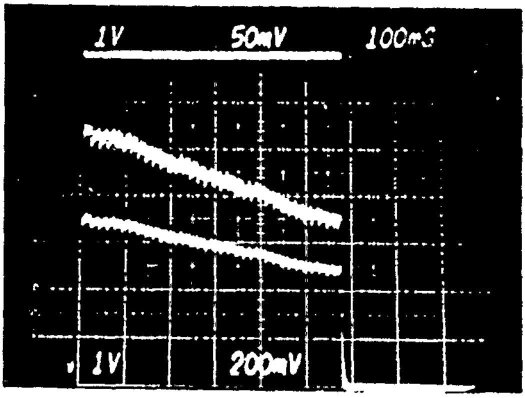


Figure 4. Constant potential kV waveform. Upper trace is the kV at 10 kV/div. Middle trace is the radiation waveform. Lower trace is the mA(continuously falling load) at 50 mA/div.

factors is to be expected.

EXPOSURE SWITCHING

With modern xray generators tremendous amounts of power are switched on and off during an exposure. Typically, 30 kW to 100 kW must be rapidly applied to the x-ray tube within a very narrow time frame. Instantaneous switching of large voltages can produce large current surges in the primary circuit and voltage overshoots in the high tension secondary.[3] These adverse effects can be reduced by loading one or more phaseswith a surge resistor at the initiation of the exposure, then shunting the resistor after a predetermined interval (Figure 5).

This method of exposure contacting is essential for mechanical type contactors, which, due to mechanical inertia, cannot be made to close precisely at a zero crossing of the primary voltage. The result is a step start with the kV maintained at a lower potential until the surge resistor is switched out [Figure 6 (a)]. With some generators, the value of the surge resistor is constant, and there fore, the voltage dropped across the resistor is dependent upon the tube load. As a result, the voltage associated with the initial step will depend upon the tube load. In Figure 6(b) are shown three Phototimed kV waveforms obtained with tube loads of 50 mA, 100mA, and 380 mA, respectively. As expected, the higher the tube load, the greater the voltage dropped across the surge resistor, and the lower the voltage in the initial step on the kV waveform.

Even with solid state exposure contactors, some surge supression is required to avoid large overshoots in the kV at the start of the exposure (Figure 7). This is especially important if the x-ray generator is to be used for high kV applications such as chest radiography. The waveform in Figure 7, taken at acceptance testing of a unit which would be utilized for chest radiography, shows that the peak voltage is several kV higher than the maximum rated tube potential of 150 kV. If allowed to continue, this condition could promote instability and arcing in the x-ray tube, leading to premature failure.

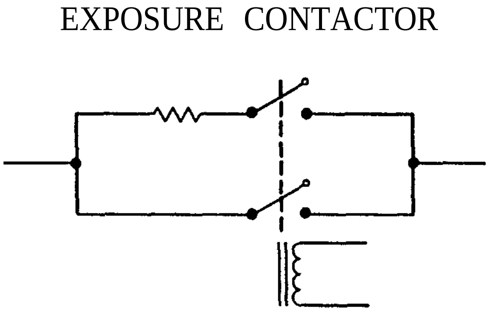


Figure 5. Surge suppression circuit(3). When the exposure is initiated the upper contactor makes first and the full power is not applied because of the surge resistor. The lower contactor then makes, shunting the resistor. This circuit reduced[8] current surges and voltage overshoots at the beginning of the exposure.

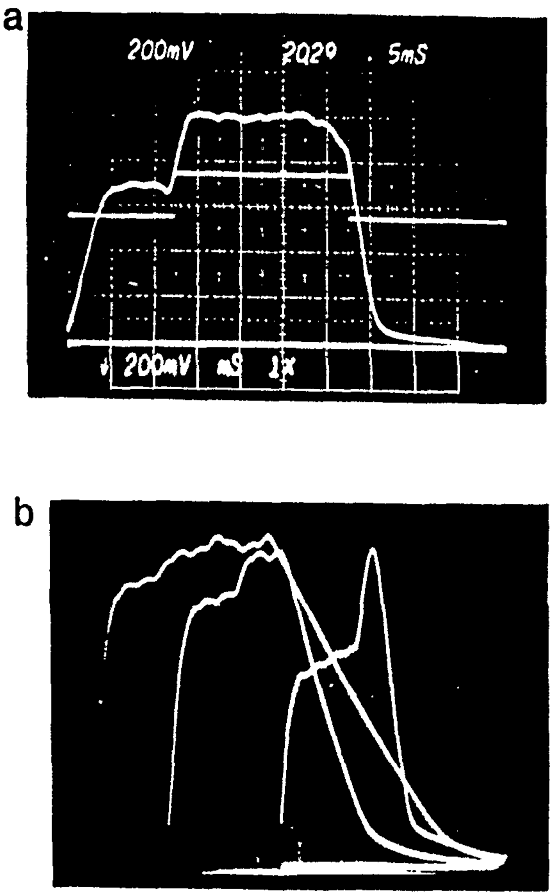


Figure 6. "Step start" of kV waveform due to surge Suppression ciucuitry. Figure 6(a): kV waveform for 100 kVp, 250 mA. The broken horizontal line is a gated signal which depicts the exposure time as defined at 75% of the kVp. Figure 6(b): kV waveforms at 150 kVp with different mA settings. Left, 50 mA; middle, 100 mA; right, 380 mA. Vertical sensitivity of 20 kV/div. Note that the kV during the initial step is highly dependent on the x-ray tube current.

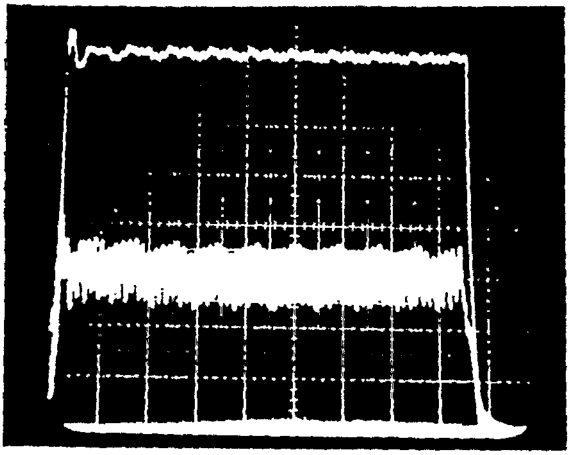


Figure 7. kV overshoot at the start of the exposure. Generator set at 150 kVp, 50 mAs. Upper waveform is the kV at 20 kV/div. The lower waveform is the tube current at 100 mA/div.

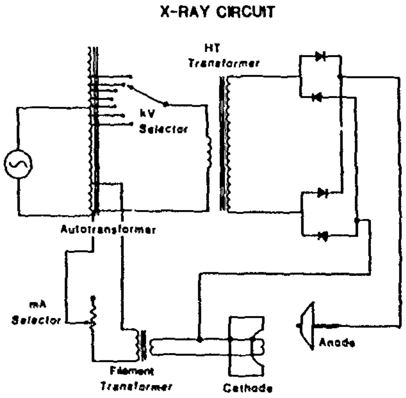


Figure 8. Simplified schematic diagram of a single - phase x-ray circuit. The primary power supply is directed, through the autotransformer, to the filament transformer and to the high tension (HT) transformer. For three-phase generators, three autotransformers, three high tension primary windings, three high tension secondary windings, and twelve rectifiers are required.

XRAY CIRCUITRY

Figure 8 is a simplified diagram of an x-ray circuit which illustrates the fundamental requirements for the production of diagnostically useful x-rays. The primary purpose of the x-ray generator is to provide the radiographer with the means of consistently providing reproducible x-ray exposures of predetermined quality and quantity. Secondarily, the x-ray generator must provide constraints on the predetermined exposure factors, in order to prevent damage to the components of the x-ray tube. The x-ray tube is a thermonic diode with positive potential on the anode and negative potential on the cathode. Voltage is supplied to the x-ray tube via transformation of primary potential. X-rays are produced when electrons, made available by thermonic action in the filament, are accelerated across the applied potential, acquiring kinetic energy which is converted to X-radiation in the tungsten target. Heating of the filament is accomplished by current flow which is solely dependent on the applied filament voltage. Quality and quantity of radiation are determined by the potential applied across the x-ray tube and the filament current. The peak tube potential can be altered by changing the primary voltage applied to the high tension transformer. The filament current can be altered by changing the voltage applied to the primary of the filament transformer. Shown schematically are the components of a single phase generator. For three-phase generators, three autotransformers, three high tension primary windings, three high tension secondary windings, and 6 or 12 rectifiers are required.

For any generator, calibration of kV and mA refers to the adjustment of internal compensating networks which function to assure that filament temperature and primary voltage to the high tension transformer will result in an x-ray tube potential and current closely corresponding to the values preselected at the control desk. Calibration is important to assure that radiation quality and quantity can be accurately set prior to making the exposure. An important part of generator calibration involves the adjustment of tube overload protection circuitry. This circuitry is designed to inhibt radiographic exposures for any combination of kV, mA, and exposure time which exceeds the instantaneous heat loading of the x-ray target. Additionally, the generator must limit the maximum filament current, in accordance with manufacturer’s specifications, since high currents result in very high filament temperatures and rapid deterioration of the filament.

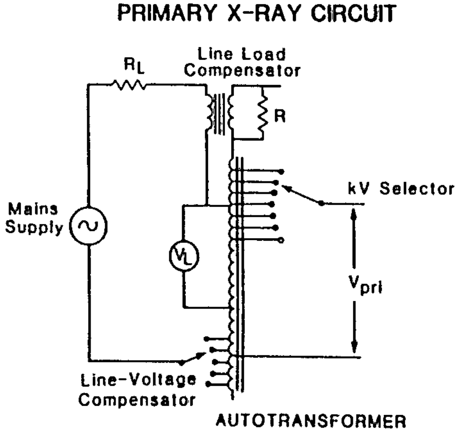


Figure 9. The primary x-ray circuit must contain means to maintain the voltage applied to the autotransformer whenever the mains supply changes (line voltage compensator), or to compensate for line losses during the actual exposure (line load compensator).

THE PRIMARY XRAY CIRCUIT

The basic components of the primary x-ray circuit are illustrated in Figure 9. Voltage to be applied to the primary of the high tension transformer is derived from the main supply via the autotransformer. This allows operator control of the kV applied to the x-ray tube, by varying the taps on the autotransformer. Alternately, the taps could be replaced by a moving contact forming a variac autotransformer. Kilovoltage calibration consists of those adjustments which assure that the primary voltage will result in the selected kV. Note, however, that if a tap is selected, and the main supply voltage changes, the primary voltage will also change, and the selected kVp will not be obtained. Therefore, it is necessary that means be available to monitor the line voltage and compensate for gradual changes in supply voltage throughout the day. Line-voltage compensation may be manual or automatic.

Loss of voltage to the autotransformer will also occur during the exposure as current flows through the inherent line resistance. Typically, line resistance ranges from 0.2 ohms to 0.5 ohms.[3] A primary current of 100 amperes will result in a 20 to 90 volt drop in the power line. Not only would this loss affect the kilovoltage obtained, but it would also change the voltage applied to the filament transformer. The effect on the filament current and, therefore, the mA, would be disastrous. Since the loss of voltage is proportional to the current in the power line, a transformer with primary windings in series with the power line can be accurately measured and additional resistance added to bring the total to that used during factory calibration. For 3-phase generators it is necessary that this adjustment be accurately performed for each phase. Failure to balance the line resistance in three-phase generators will result in distortion of the kV waveform- The greatest effect, however, will be in the filament supply, which must be highly regulated.

THE FILAMENT CIRCUIT

The current through the filament of any x-ray tube is determined by the applied voltage. A small change in filament current will result in a large change in the x-ray tube current (Figure 10). For example, at 90 kVp a change in filament current from 4.58 A to 4.80 A (+4.9%) will result in a change in tube current from 300 mA to 500 mA (+67%). It is thus imperative that the filament current and, therefore, the filament voltage be highly regulated.

Even if the filament voltage were maintained at a constant value, the tube current would not remain constant if the tube potential is changed. As shown in

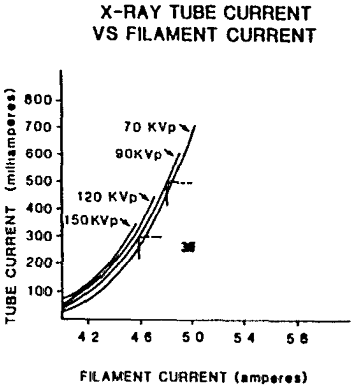


Figure 10. X-ray tube current as a function of the filament current for various tub5 voltages. Note that a relatively small change in filament current will produce a large change in tube current.

Figure II, changes in tube voltage for a fixed filament current will result in corresponding changes in the x-ray tube current. This is because as the x-ray tube potential is increased, additional electrons are drawn from the “space charge” surrounding the hot filament. Because of this phenomenon, compensation must be provided so that x-ray tube current will I closely correspond to the selected value, regardless of the kV applied to the x-ray tube. The x-ray filament Circuit (Figure 12) must therefore provide means of preselecting the desired tube current and compensating for external factor5 that act to alter the current.

Maintaining the filament at a high temperature for prolonged period’s of time can result in vaporization of tungsten and rapid deterioration of the filament. Therefore, the filament current required for the exposure is applied only during “preparation”, the interval during which the anode is made to rotate at its minimum required rotational velocity. During preparation, the filament current is determined by the voltage applied to the filament.. This voltage is not applied directly from the autotransformer, but rather a voltage is obtained from the autotransformer and applied to a constant voltage transformer. The constant voltage transformer is designed to maintain the output voltage to a very close tolerances, regardless of any fluctuations in the primary voltage. Part of the output from the constant voltage transformer is absorbed by a resistor (Figure 12). A variable resistor is connected in series to provide an adjustment for filament voltage. Adjustment is necessary to compensate for changes in resistance as the filament deteriorate5 with use. This is called a “pre-heat” adjustment because it determines the filament current and therefore the filament temperature prior to making the exposure.

The filament voltage must be compensated to correct for changes in tube current which would result as the kV across the x-ray tube is changed (i.e., space-charge compensation). This can be accomplished by adding or subtracting filament voltage as the kV is changed. In Figure 12, note that for KV values below the value corresponding to zero compensation, a positive voltage is added to the filament circuit. This results in a larger filament current to compensate for the decreases in tube current which would occur as the kV is reduced. As the kV is increased, voltage is subtracted from the filament circuit. It should be noted that when making a space-charge compensation adjustment during calibration, the goal is to obtain the same mA value throughout the range of useful kV’s. Also, because space charge effects are greater at high filament temperature (Figure 11), a space charge compensation should be adjusted at a relatively high mA, typically 500 mA, It is INCORRECT to adjust space charge compensation by merely setting a high kV and

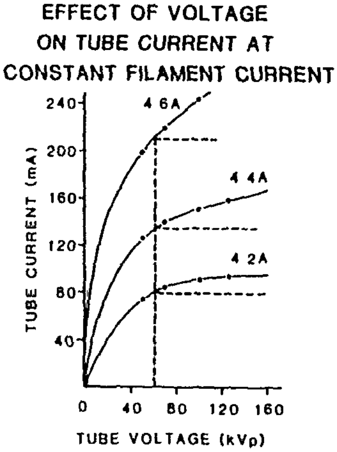


Figure 11. X-ray tube current as a function of tube voltage for various fixed filament current values.

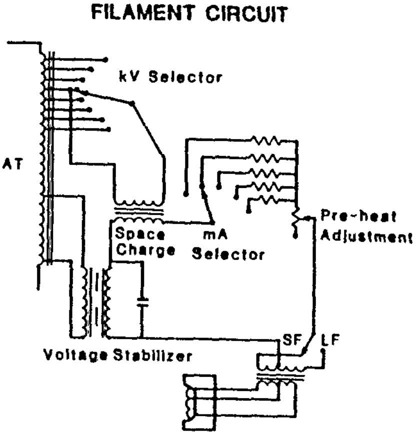


Figure 12. Schematic diagram of the x-ray filament circuit.

making the space charge adjustment to provide an mA value equal to that at the generator. Proper space charge adjustment is made by measuring the mA at a low kV (60 kvp), and also at high kV (140 kVp), and adjusting the space charge compensation to provide the SAME mA, regardless of whether the mA corresponds to the value set. If, after the space charge adjustment, the mA is not correct, the pre-heat and mA stabilizer should be adjusted.

The voltage applied to the x-ray tube is not dependent solely on the value of the voltage applied to the primary of the high tension transformer. Voltage losses occur across the internal resistance of the primary winding, and the amount of the loss varies as the primary current is changed. It is therefore necessary that the primary voltage, which is applied to the high tension transformer prior to the exposure, be higher than that which would be required if there were no internal losses. For example, referring to Figure 13 at 200 mA a primary voltage of 200 volts would result in 80 kVp at the x-ray tube. If the mA were changed to 1,000 mA, with no change in the value of primary voltage, the resultant secondary voltage would only be 50 kV. The primary voltage would have to be increased to 274 volt5 in order to maintain the x-ray tube potential at 80 kVp. The x-ray generator must therefore provide kV compensation for changes in tube load. It should be noted that the load lines in Figure 13 are not parallel, and larger changes in primary voltage for a given change in tube current are required at high kVp as compared to a lower kVp. A necessary part of x-ray generator calibration therefore is adjustment of the kV compensation for tube loading.

Shown in Figure 14 are two kV waveforms obtained at a setting of 80 kVp. The left waveform was obtained at 100 mA and the right waveform at 700 mA. As shown, kV compensation for the load was insufficient to maintain the peak kilovoltage as the tube current increased. This is the case corresponding to correct adjustment of the filament current but with inadequate compensation of the primary voltage. Conversely, the primary voltage can be correctly adjusted, according to the intended value of tube current, but, if the filament current were incorrectly set, the wrong tube potential would be obtained. That is, the wrong filament current would produce the wrong mA, and from Figure 13, the value of tube voltage obtained would not correspond to the value selected. This condition is dramatically illustrated whenever the filament pre-heat is incorrectly adjusted. For the waveforms shown in Figure 15 (a), the filament current and therefore filament temperature was too low at the beginning of the exposure but then increased to the correct value by action of the mA stabilizer. The primary voltage, on the other hand, was correc, assuming

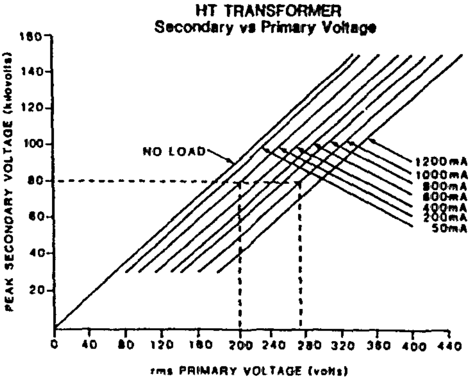


Figure 13. X-ray tube potential as a function of the primary voltage applied to the high tension transformer and the tube load(mA)

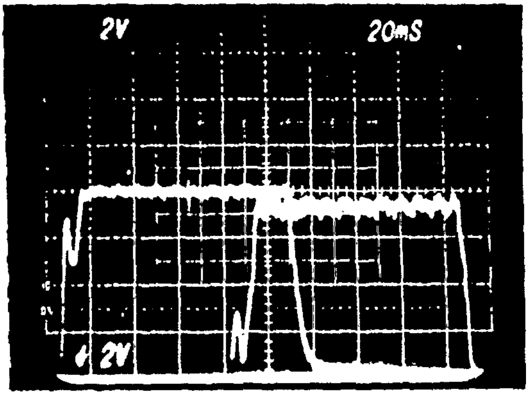


Figure 14. Waveform obtained at 80 kVp. Left: tube load of 100 mA, right: tube load of 700 mA. kV compensation for the load was inadequate to maintain the tube potential as the tube current was increased.

the tube current corresponded to the value which was selected. Because the tube current was low at the beginning of the exposure, the resultant x-ray tube potential was too high. Merely adjusting filament pre-heat therefore will correct both the low mA value and the high kV value at the beginning of the exposure [Figure 15 (b)].

Another problem, very much resembling the results of incorrect pre-heat adjustment, is associated with the thermal inertia inherent in the filament. Filament temperature cannot instantaneously change from one value to another, but changes only gradually. Thus, it is possible that both the filament current and the primary voltage to the high tension transformer are correct, but the waveforms will indicate otherwise if the exposure is initiated before the time required to achieve proper filament temperature. This condition is illustrated by varying the length of the preparation phase of the exposure (Figure 16). The waveforms on the left were obtained by pushing the exposure switch all the way to the expose position so that the exposure is released as soon as the anode has reached its minimum rotational velocity. The middle waveforms were obtained by holding preparation until hearing the audible sound of the exposure release relay, and then completing the exposure. The waveforms on the right were obtained by holding preparation for 2 seconds before completing the exposure. Holding the preparation phase for longer intervals resulted in no further changes in the waveforms. Thus, the filament pre-heat and primary voltage were correctly adjusted, but the preparation phase of the exposure initiation was not long enough to allow the filament temperature to change from the ambient value to that required for the exposure. This condition can be corrected by either increasing the ambient temperature (i.e., the standby filament current), or increasing the time delay before exposure release.

In general, the kV applied to the x-ray tube should consist of equal amplitude pulses whose peak value corresponds closely with that set at the control desk (Figure 17). Large deviations from the nominal kV ma adversely affect the quality of the resultant radiograph[4] and should be corrected, if possible. The origin of such deviations varies widely but a few characteristic causes have been identified. For example, Figure 18 (a) and (b) show periodic drops in the tube voltage which occur every 1/60th second, and which gradually decrease in magnitude. Such a pattern is usually associated with losses of magnetic flux in the high tension transformer. This can occur, for example, if the core becomes magnetically saturated. Pre-magnetization of the core and phase sequencing are often employed to reduce this effect. Figure 18(c) and (d) show kV waveforms which each have Only one dip in the kV, occuring near the beginning of

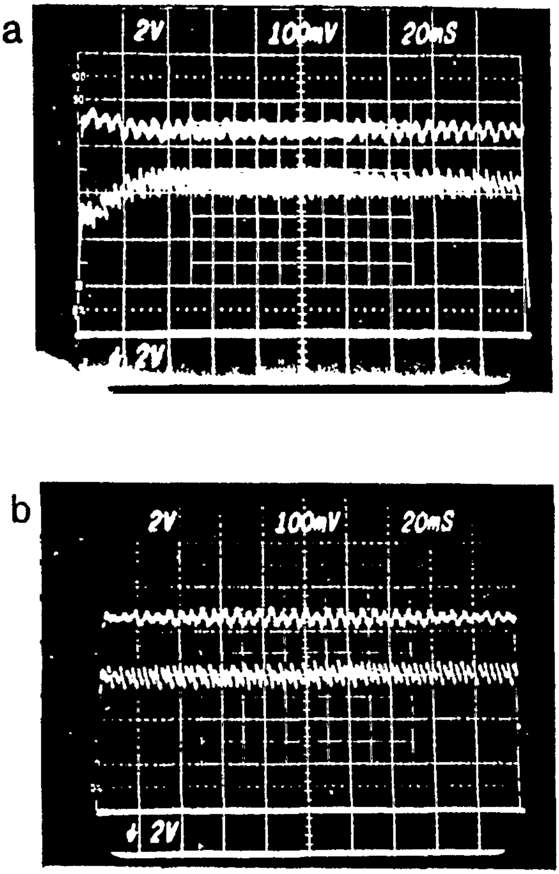


Figure 15. kV and mA waveforms obtained at 90 kVp and 400 mA. (a) Incorrect pre-heat adjustment resulting in the mA being too low and the kV too high at the beginning of the exposure. (b) Adjustment of filament preheat corrects both the mA and kV since the primary voltage applied to the high tension transformer was already correct. The kV waveform is displayed at 20 kV/div. and its baseline is the second horizontal gradicule. The mA waveform is displayed at 100 mA/div. and its baseline is the first horizontal graticule.

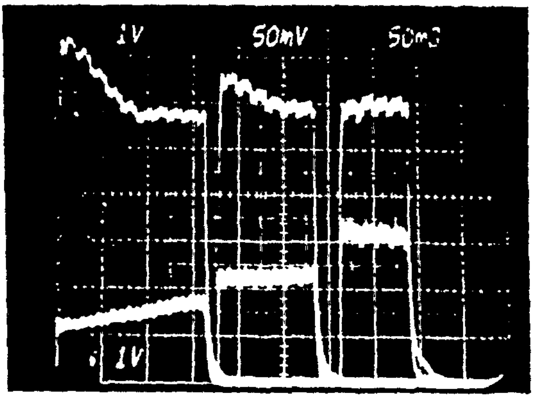


Figure 16. kV (upper) and mA (lower) waveforms from a generator set for 60 kVp, falling load. Left: Exposure switch fully depressed so there was no delay in the exposure release. Middle: Preparation held until just after the exposure release relay was energized. Right: Preparation held for 2 sec before completing the exposure. These demonstrate that the filament current and primary voltage were correct, but that the filament was not reaching the required temperature before the exposure was released.

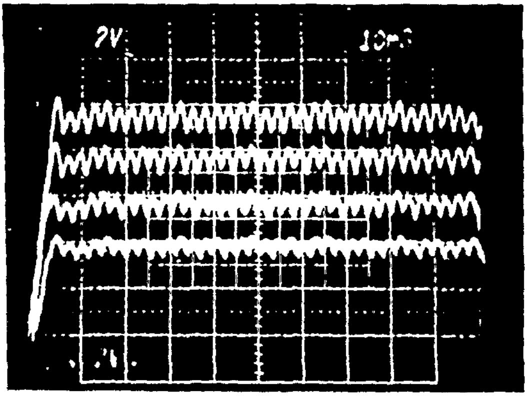


Figure 17. kV waveforms displayed at 20 kV/div.(vertical) and 10 msec/div.(horizontal). Exposures were made at console settings of 60, 80, 100 and 120 kvp. Note that these waveforms demonstrate little overshoot and nearly equal amplitude pulses whose maximum value remains constant throughout the exposure.

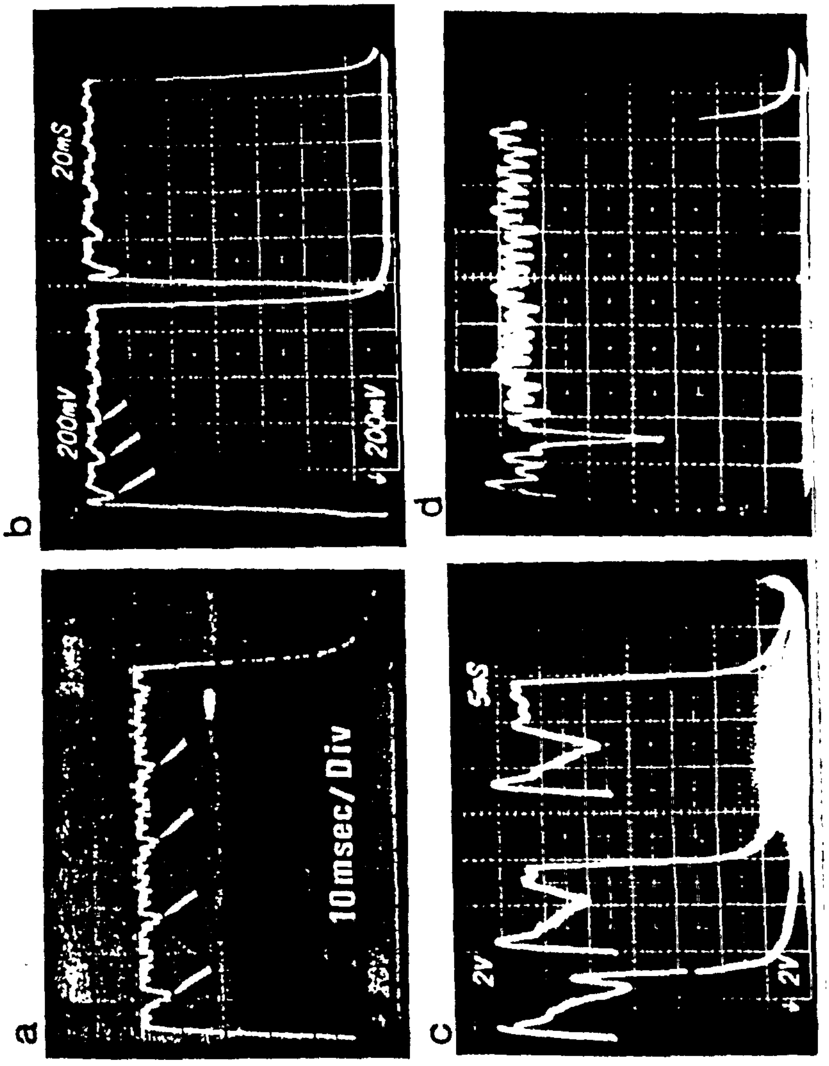


Figure 18. Waveforms which demonstrate some abnormal deviation from the nominal tube voltage. Figure 18(a) and (b) show the result of core saturation which causes a loss of magnetic flux in the transformer core. Note that the drop in potential occurs every 1/60 second(arrows) and gradually diminishes as the exposure continues. The waveforms in Figure 18(c) show a very large drop in the tube voltage due to poor synchronization of the exposure with the line voltage. The loss of voltage in Figure 18(d) is due to contactor bounce.

the exposure. For Figure 18 (c), the loss of potential was found to be related to the synchronization of the exposure with the line voltage, and was corrected by adjustment6 in the exposure timing circuits. The voltage drop in Figure 18 (d) was due to contactor bounce. Contactor bounce can occur not only in the “make” contacts, but also in contactors associated with exposure inhibit circuitry. For example, this particular problem occured in a contactor which was designed to inhibit the exposure until after the stator current had dropped to a level indicating that the anode was rotating at its nominal velocity.

Large deviations from the nominal kV will aslo occur with the loss of one phase in a three phase generator. This result6 in a nearly single phase appearance of the kV waveform (Figure 19). In this instance, one phase was lost when one of the main line contactors broke off. Less severe variation6 of this form of voltage loss will occur if the voltage of one phase is considerably less than that of the other two phases. This situation can occur if the line resistance is not properly adjusted, if the line voltage is low on one phase, or if the tap on the autotransformer for one phase is improperly set.

The voltage applied to the x-ray tube should be evenly distributed between the cathode and anode, such as that illustrated in Figure 20 (a). In this figure the upper trace is the anode voltage and the lower trace is the cathode voltage for a tube potential corresponding to 81 kVp. It should be noted that these waveforms are displayed at 20 kV per division, and that each reaches a peak of approximately 46 kVp, which is considerably larger than half of the 81 kVp set at the control desk. This does not mean that the voltage was out of calibration, but illustrates the fact that anode and cathode voltage must be added vectorially, since they are 30 degrees out of phase. Note that a peak occurs in the anode voltage at the instant that a valley occurs in the cathode voltage. Addition of the two waveforms thus results in the correct kVp, with a simultaneous reduction in the total ripple [Figure 20(b)]. An exception to this occurs, for example, with the General Electric AMX-110 mobile radiographic generator. Shown in Figure 21 on the right is the cathode voltage (upper trace) and the anode voltage (lower trace). Note that the anode and cathode are in phase; thus, the composite voltage waveform (left trace) is equal to twice the voltage applied to either the anode or cathode alone. Note also that the voltage ripple is also twice that associated with either electrode alone.

These effects must be taken into account when a voltage divider is used to monitor the kV during calibration procedures. Insertion of only the anode side of the voltage divider into the circuit will generally not produce a voltage waveform whose peak value is

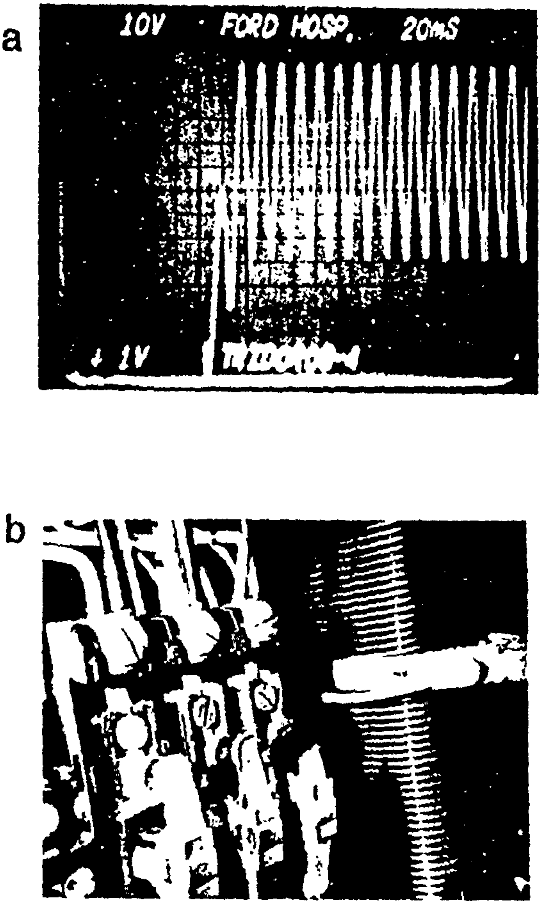


Figure 19. A three-phase generator produced a waveform(a) which appears to be that form a single-phase generator. The problem was traced to a loss of one phase when a main line contactor broke off(right-hand contactor in (b)).

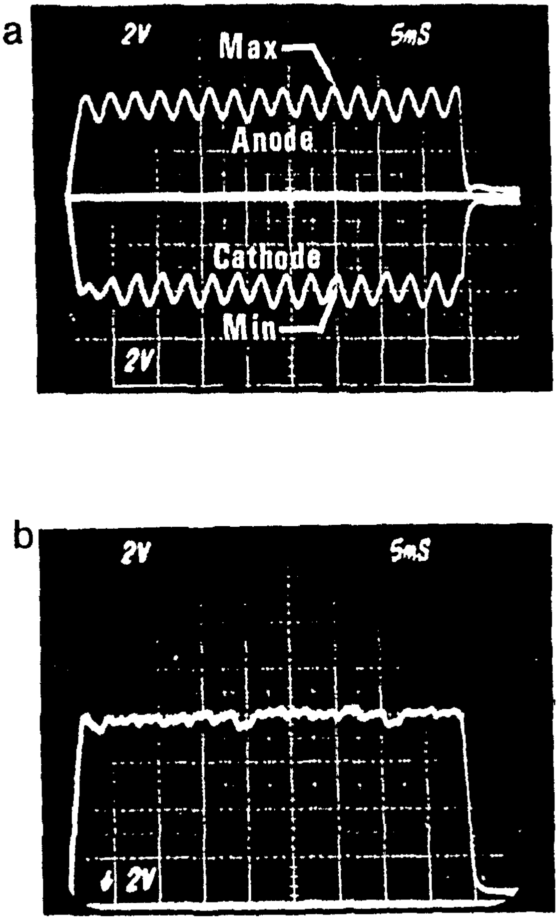


Figure 20. Anode and cathode voltages must be added vectorially since they are 30 degrees out of phase. Note that in Figure 20(a) a maximum occurs in the upper trace (anode voltage) at the same instant that a minimum occurs in the lower trace (cathode voltage). Thus, the composite voltage (Figure 20(b) is less than the sum of the two peak values and also the net ripple is lower. Vertical sensitivity 20 kV/div.

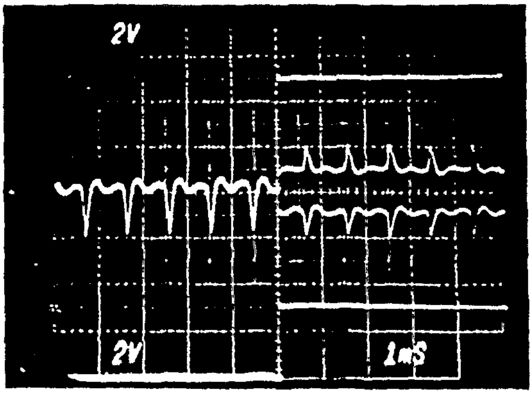


Figure 21. Left: Composite tube voltage produced by a frequency invertor mobile radiographic generator. Right: Cathode voltage (upper trace) and anode voltage(lower trace). Note that the anode and cathode voltages are in phase. Thus, the net peak kV is the simple sum of the two Voltages and the net ripple is greatly increased.

exactly half the nominal value set at control desk.

As mentioned earlier, x-ray tube potential can be controlled by triodes in the high tension secondary 50 as to provide nearly constant potential to the x-ray tube (Figure 22). With this type of generator, a very high potential (from 180 kV to 220kV, depending upon the tube voltage and current selected) is applied across the triode. The grid of the triode is electronically control led, and the triode becomes a variable resistor capable of absorbing large voltages almost instantaneously. Thus, x-ray tube potential can be maintained to nearly a constant value, regardless of the size of the tube load. In other words, kV compensation for a load is virtually instantaneous and extremely large amounts of power can be switched very rapidly. A6 noted and illustrated previously (see Figure 4) this type of high voltage control is ideal for falling load generators.

THE FALLING LOAD TECHNIQUE

The principle of the falling load technique (Figure 23) is that the tube current start5 at a rather high value, then continuously falls throughout the exposure. If the falling mA curve were selected so as to maintain the anode temperature at the maximum allowable limit, then for any given mAs, the exposure time will theoretically be the shortest time possible. In Figure 23, from the conventional loading curve, the shortest possible exposure time for a 50 mAs exposure is 0.1 seconds. For 120 mAs, the shortest possible exposure time is 0.3 seconds, corresponding to 400 mA. Note, however, that if 400 mA were set but only 50 mAs were required, the exposure time would have to be 125 msec, which is 25% longer than necessary. To consistently obtain the shortest time, the radiographer would have to consult the tube loading chart for every exposure in order to determine the maximum allowable mA for the mAs value required.

To alleviate this requirement the falling load curve is constructed such that, for any given exposure time the mAs obtained is equal to the maximum allowed mAs. For example, at a tenth of a second the maximum allowed mAs is 50 mAs. Similarly, for the 0.3 second exposure the maximum mAs is 120, and for the falling load curve the area under the curve for a 0.3 second exposure is also 120 mAs. Thus, regardless of the exposure time the maximum available mAs is utilized and, therefore, the exposure time is always minimized.

Since the falling load curve always produces maximum mAs regardless of the exposure time, it is identical to the maximum kW loading curve of the anode. In general, the kW of an x-ray tube is defined for each focal spot as the product of the maximum mA times the corresponding kV

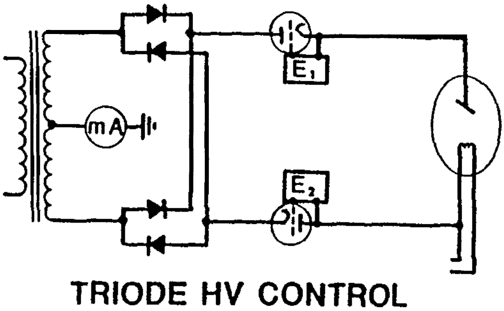


Figure 22. Simplified schematic of high tension secondary with triodes to control the voltage applied to the x-ray tube. The triodes act as variable resistors which absorb any variations in the transformer output, thus maintaining a constant potential on the x-ray tube.

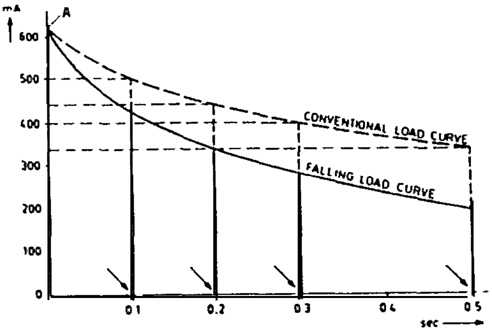


Figure 23. Comparison of the conventional anode loading curve with the falling load curve. For any given exposure time, the area under the falling load curve is equal to the product of the exposure time multiplied by the maximum mA allowable from the conventional loading curve.

at 0.1 seconds. One can also obtain the complete kW loading curve by plotting the kW loading (kV x maximum mA) as a function of the exposure time. It can be derived from the anode loading curves (Figure 24) by selecting one of the curves and calculating the kW as a function of exposure time. It should be noted that the kW for a given exposure time is independent of the particular kV selected, with the exception of low kV values, where the maximum tube current is limited by a restriction on the maximum temperature of the filament, rather than on the temperature of the x-ray target. These limits are indicated by the truncated curves at low kV. The resultant kV curve vs. exposure time (Figure 25) can then be used to evaluate whether the falling load circuitry is maintaining a consistent degree of tube loading, without exceeding the thermal limits of the anode.

It should be noted that it would not be possible to use the maximum anode thermal rating for every exposure, since these ratings are based upon a cold anode. If the maximum allowed exposure were always utilized residual heat in the anode would soon raise the temperature of the target to a high level, and if the next exposure were also a maximum anode load the temperature of the focal spot might exceed the melting temperature of tungsten. Therefore, falling load curves are not set to maximum but rather some percentage of maximum, typically 65%.

To evaluate whether a given falling load curve maintains a fixed percentage of tube load throughout the exposure, the following procedure can be utilized (Figure 26):

1. Select the focal spot and kV and make a low mAs, short time exposure. Measure the exposure time, the mAs, and the maximum mA at the start of the exposure.

2. Verify that the maximum mA measured does not exceed the maximum mA allowed for the kV which is selected.

3. From the kW loading curve find and record the maximum kW divided by the kV.

4. Calculate the maximum allowed mA which is equal to the maximum kW divided by the kV.

5. Calculate the maximum allowed mAs, which is equal to the mA times the exposure time measured.

By comparing the calculated maximum mAs to the actual mAs measured, one can calculate the mAs measured as a percentage of the maximum allowed mAs. This procedure can be repeated, using progressively larger mAs values, to assure that the percent of the maximum mAs remains relatively constant. (See Figure 26).

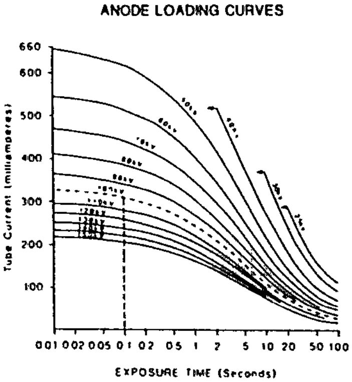
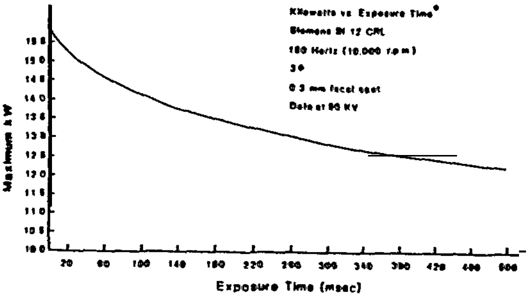
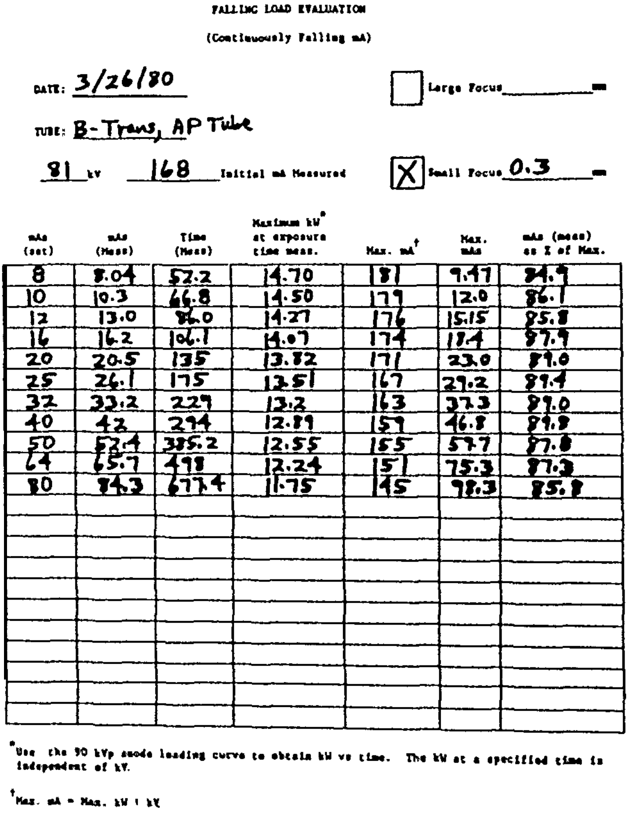


Figure 24. Conventional anode loading curves. In general, the kW for a given focal sopt is defined as the product of kV and the maximum allowed mA for a 0.1 sec. exposure. This is often calculated at 100 kV for convenience.



*For any given exposure time the kW is independent of the kV

Figure 25. kW loading curve. The curve is derived from the product of kV and maximum allowed mA for a given exposure time, and is independent of the kV, except where the mA is limited by the maximum filament current.



FALLING LOAD EVALUATION

(Continuously Falling mA)

DATE: 3/26/80

☐ Large Focus ______ mm

TUBE: B-Trans, AP Tube

81 kV 168 Initial mA Measured

☒ Small Focus 0.3 mm

mAs (set)	mAs (Meas)	Time (Meas)	Maximum kW* at exposure time meas.	Max. mA†	Max. mAs	mAs (meas) as % of Max.
8	8.04	52.2	14.70	181	9.47	84.9
10	10.3	66.8	14.50	179	12.0	86.1
12	13.0	86.0	14.27	176	15.15	85.8
16	16.2	106.1	14.07	174	18.4	87.9
20	20.5	135	13.82	171	23.0	89.0
25	26.1	175	13.51	167	29.2	89.4
32	33.2	229	13.2	163	37.3	89.0
40	42	294	12.89	159	46.8	89.8
50	52.4	385.2	12.55	155	59.7	87.8
64	65.7	498	12.24	151	75.3	87.3
80	84.3	677.4	11.75	145	98.3	85.8

*Use the 90 kVp anode loading curve to obtain kW vs time. The kW at a specified time is independent of kV.

†Max. mA = Max. kW ÷ kV

Figure 26. Data form for evaluation of the continuously falling load technique.

Another form of “falling load” actually consists of a series of stepped constant loads6 (Figure 27). In the case shown here, the kV compensation for load is not properly adjusted and the kV does not remain constant as the tube current is stepped to a lower value. It should be noted that the primary voltage is instantaneously reduced to that required for the lower tube current in each step, whereas the thermal inertia of the filament does not allow the filament to cool instantaneously to the temperature corresponding to the lower mA. As a result, the mA slowly drops between steps. Thus, at the beginning of the second step the tube load is too high for the new primary voltage, and the kV rapidly drops. As the mA changes to the lower value, the kV rises to the nominal value obtained in the second step. Figure 28 is a kV waveform with properly adjusted kV compensation for load, thus providing the same nominal kV value through the exposure. Also, the exposure is briefly terminated between steps to allow the filament to cool to the temperature corresponding to the lower mA in the second step. In this way, the effects of the thermal inertia are reduced. Figure 29 illustrates a method of evaluating the step-wise falling load. From the tube loading chart, the maximum mA at 0.1 seconds is obtained for the kV value used in the exposure. The kV is evaluated at the beginning and ending of each step and expressed as a percentage of the set kVp. The mA at the beginning and ending of each step is also recorded and expressed as a percentage of the maximum allowable mA.

TUBE CURRENT WAVEFORMS

As previously illustrated, occilloscope display of the tube current waveform is very useful in evaluating generator performance. The use of a Machlett Dynalyzer™ high voltage measuring instrument provides simultaneous kV and mA waveforms. In addition, the filament current may be monitored and displayed using this device. However, there are instances when other voltage dividers are used which do not provide this capability. In such cases, the mA waveform is observed by inserting a precision 10 ohm resistor in the mA metering circuit and displaying the voltage drop across the resistor on a storage oscilloscope. For example Figure 30(a) is the mA waveform obtained on a G.E. AMX-110 mobile radiographic unit. Unfortunately, with this type of display it is difficult to determine the average tube current. Therefore, a method of filtering the mA waveform to accurate1 obtain the average tube current has been developed.[7] This method is in excellent agreement with more conventional means of measuring tube current, such as a digital mA meter. The advantage, however, is that the average current can be obtained using short exposure times.

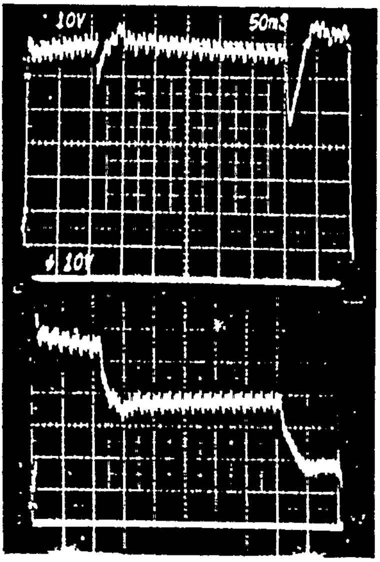


Figure 27. Example of a "falling load" which is actually a stepped, constant mA. Upper: kV waveform (l0kV/div.). Lower : mA waveform (200 mA/div.). Note that the mA is reduced in three consecutive steps, each of which provides a relatively constant mA. The kV does not remain constant, especially at the transition between steps, because of the thermal inertia of the filament and inadequate kV compensation for load.

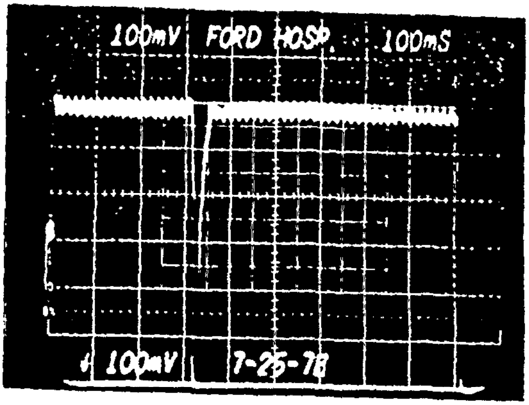
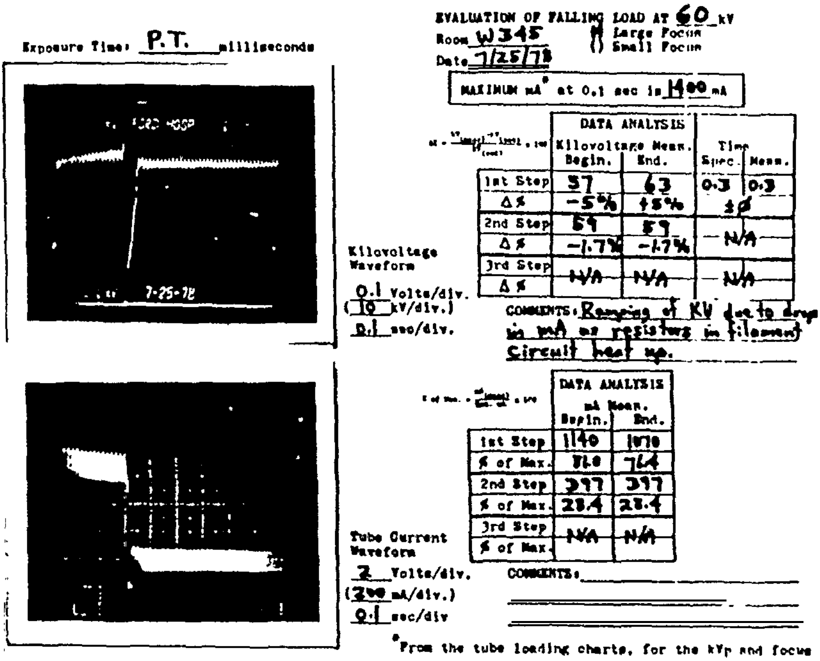


Figure 28. kV waveform for falling load(stepped constant mR) with good kV compensation for load. The exposure is automatically terminated between steps to allow for the filament to cool to the temperature corresponding to the lower mA. Thus, the effect of thermal inertia is reduced.



EVALUATION OF FALLING LOAD AT 60 kV

Room W345

Date 7/25/78

☒ Large Focus

☐ Small Focus

Exposure Time: P.T. milliseconds

MAXIMUM mA* at 0.1 sec is 1400 mA

$\Delta\% = \frac{kV_{(meas)} - kV_{(set)}}{kV_{(set)}} \times 100$

	DATA ANALYSIS Kilovoltage Meas. Begin.	 Kilovoltage Meas. End.	Time Spec.	Time Meas.
1st Step	57	63	0.3	0.3
Δ%	-5%	+5%	±0	
2nd Step	59	59	N/A	
Δ%	-1.7%	-1.7%		
3rd Step	N/A	N/A	N/A	
Δ%				

Kilovoltage Waveform

0.1 Volts/div.

(10 kV/div.)

0.1 sec/div.

COMMENTS: Ramping of KV due to drop in mA as resistors in filament Circuit heat up.

$\% \text{ of Max.} = \frac{mA_{(meas)}}{Max.\ mA} \times 100$

	DATA ANALYSIS mA Meas. Begin.	 mA Meas. End.
1st Step	1140	1070
% of Max.	81.4	76.4
2nd Step	397	397
% of Max.	28.4	28.4
3rd Step	N/A	N/A
% of Max.		

Tube Current Waveform

2 Volts/div.

(200 mA/div.)

0.1 sec/div

COMMENTS:

*From the tube loading charts, for the kVp and focus

Figure 29. Form for evaluation of falling load waveforms with stepped constant loads.

Figure 30(b) is a typical mA waveform from a three-phase generator. The large spike at the beginning of the exposure is not abnormal: it is the initial surge of current which charges the inherent capacitance of the high tension cables. It can be easily distinguished from an overshoot in mA which is due to incorrect pre-heat adjustment, since its duration is only 1 to 3 milliseconds, whereas an mA overshoot will last several tens of milliseconds.

The inherent capacitance of the high tension cables will also prevent instantaneous removal of the voltage across the x-ray tube, with the result that the mA (and kV) waveforms will gradually, rather than instantaneously, drop to zero following termination of the exposure. This effect, as well as the effect of a surge suppression step in the kV and mA waveforms, presents a problem with the measurement of mAs. Generally, mAs is measured by inserting an integrating coulomb meter (mAs meter) in series with the mA metering circuit. However, the meter will integrate all signal present, including the area under the initial step, and the capacitive tail. Thus, the measured mAs will be larger than that calculated from the product of mA x exposure time. This discrepancy will be especially severe for short exposures since the initial step and the discharge tail will be a larger percentage of the useful mAs value. For this reason, the use of a mAs meter during generator calibration is not recommended except for generators which do not provide independent selection of mA and time, but only the product of these two. Observation of the mA waveform is preferred since it will provide direct measurement of mA and it may also help to identify the cause of abnormal generator performance.

MULTIPLE TUBE INSTALLATIONS

The discussion thus far has assumed that the generator is used to control only one x-ray tube. If this is the case, the generator will probably have sufficient calibration adjustments available to correct any of the problems which have been presented. However, it is not uncommon for a single generator to control two or even three x-ray tubes in a given installation. In this situation, one would expect that the manufacturer would provide sufficient means to properly calibrate each tube and each focal spot on that tube. It has been shown,[8] however, that this is often not the case, especially if the tubes have considerably different design characteristics. Typical design parameters which Will affect the calibration are anode-cathode spacing, filament size, filament diameter, and cathode design. In addition, the thermal characteristics of two different tubes may vary considerably. This may require that the tube overload protection circuitry be adjusted for the

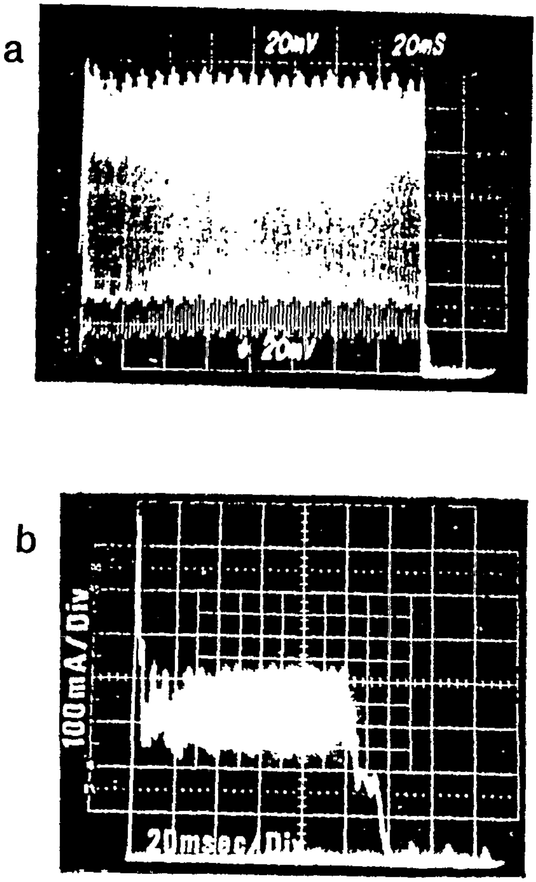


Figure 30. Tube current waveforms obtained by inserting a precision 10 ohm resistor in the mA metering circuit (a) Waveform obtained from a frequency invertor mobile generator. Note that the mA ripple makes it difficult to determine the average tube current. (b) Waveform from a three-phase generator. Note the initial spike due to the charging of cable capacitance, and the discharge tailing at the end of exposure. Both of these are normal effects.

lower capacity tube, thus limiting the maximum tube load of the other tube to only a fraction of its capacity. The lack of independent calibration adjustments for each tube may force the service engineer to compromise between the optimal settings for each tube. This can result in poor calibration of both tubes. Two tubes which are controlled by the same generator should, therefore, be of identical electrical and thermal characteristics, unless separate calibration adjustments are provided.

SUMMARY

In conclusion, one must realize that there is no such thing as the ideal generator. If it did exist, it would produce square wave kV and mA waveforms which would not deviate from the set technique (Figure 31). The exposure time would be exactly defined, and the mAs would be the simple product of (exposure time) x (mA).

Realistically,however, the kV and mA waveforms are far from ideal. The kilovoltage waveform is often characterized by a premagnetization pulse, a surge step, a possible overshoot at the beginning of the exposure, ripple, and trailing edge which gradually drops to zero volts. The mA waveform is characterized by an initial overshoot due to charging of the high tension cables, a low mA value associated with the surge step, ripple, and a gradual drop to zero mA as the capacitance of the high tension cables is discharged. Exposure time is rather arbitrarily defined in terms of threshold crossing of the kV waveform. The mAs is not well defined since the simple product of exposure time and average mA excludes tube current present during the surge suppression step and during discharge of the high tension cable capacitance. This discrepancy can lead to a large deviation between the “calculated” mAs and that measured with an mAs meter. Specification of generator calibration should take into account these limitations of x-ray generator performance. However, recognition of these limitations, and application of waveform analysis can lead to optimization of x-ray generator calibration and increase the reliability of these devices for medical diagnostic applications.

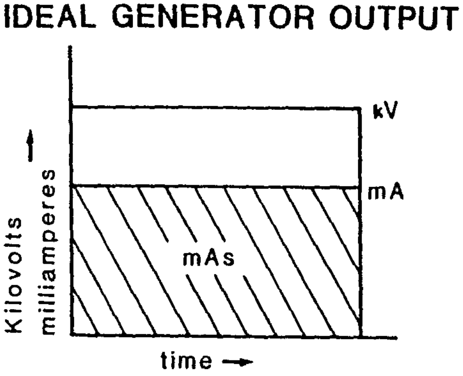


Figure 31. The "ideal" x-ray generator would produce square wave kV and mA waveforms with no deviation from the set techniques.

AUTOMATIC EXPOSURE CONTROL DEVICES

Prior to 1942, all radiographic examinations were performed on equipment which required the operator to make educated judgments with respect to the required value of tube potential, tube current, and time needed for a properly exposed radiograph. Even with the aid of technique charts these decisions were not standard for each projection, due to differences in patient density, variation in positioning, and the presence of anatomical or pathological abnormalities. As a result of these problems associated with the selection of proper exposure techniques, the need for a simple automated method of insuring consistent quality radiographs became apparent.

The initial step toward designing an automatic exposure control which would reduce much of the guesswork was introduced by Dr. Russel H. Morgan.[9] His device incorporated a fluorescent screen mounted behind the plane of the image receptor. X-rays which passed through the patient and image receptor would produce fluorescence in the screen. A phototube was optically coupled to the screen, producing a current signal which was proportional to the amount of fluorescence. The x-ray exposure time was controlled by a capacitive trigger circuit designed to terminate the exposure. whenever a pre-set level of charge was accumulated. With the help of Dr. Paul Hodges and the facilities of the University of Chicago, the first automatic exposure control device, the Morgan-Hodges Phototimer, was constructed and introduced in the late 1940's.

Today the "phototimer" has been widely accepted and has taken many forms and names depending on the type and application of the device (Table III).

Automatic exposure control (A.E.C.) will be used to refer to any device used to automatically terminate the exposure to an image receptor.

THE PURPOSE AND FUNCTION OF AN A.E.C. DEVICE

Two key purposes of an A.E.C. system can be defined:

1. The first purpose is to provide the radiologist a radiograph which will enable him to visualize patient pathology. To accomplish this, the system must reproduce results with optimum density, for any given projection and any given patient, utilizing modern image receptors, including rare earth intensifying screens.

2. The second purpose of an A.E.C. system is to simplify and speed the operation of making radiographs.

Unfortunately, not all A.E.C. systems fulfill these two purposes. To understand why, one must distinguish

TABLE III

Nomenclature For Automatic Exposure Control Devices

Radiographic Applications	Fluoroscopic Applications
Automatic Exposure Control	Automatic Exposure Rate Control
Automatic Exposure Termination	Automatic Brightness Control (ABC)
Automatic Density Control	Automatic Brightness Stabilizer (ABS)
Phototimer	
Ionization Timer	

between the purpose of an A.E.C., and its function.

The function of an A.E.C. device is fourfold:

1. Sample radiation transmitted through the patient.

2. Integrate an electrical signal which is proportional to the accumulated radiation reaching the image receptor.

3. Set a reference signal which is dependent upon the exposure factors, field size, image receptor sensitivity, and required optical density.

4. Provide a terminate signal to the generator whenever the integrated electrical signal reaches the value of the reference signal.

It is important to understand that an A.E.C. device may perform each of the four functions and still not provide clinically acceptable radiographs.

In order to obtain acceptable results, the device must be properly calibrated and the radiographer must have a clear understanding of its function so as to fully utilize it within design limitations. Calibration involves the adjustment of internal compensation networks by qualified service personnel and setting the sensitivity to a level which provides acceptable radiographic density. A number of compensation networks may be identified, and they may be grouped into INTERNAL and EXTERNAL control of sensitivity.

Internal compensation refers to changes in signal gain or reference voltage level within the A.E.C. electronics. These changes are either automatically produced in response to changes in technique factors, type of detector selected, cassette size, etc., or are adjustments to be set during calibration (Table IV).

External compensation refers to changes in signal gain or reference voltage which are produced by operator controlled sensitivity adjustments (TableV). These provide the radiographer with means to change A.E.C. sensitivity for specific examinations, to meet individual radiologist preferences, and to al low the use of two or more different image receptors. It may also be necessary to utilize external compensation to overcome design limitations which result in poor or inadequate compensation.

BASIC ELEMENTS OF AN A.E.C.

To determine the amount of radiation which reaches the image receptor, one could utilize either the ability of x-rays to cause fluorescence in selected phosphors, as did Dr. Morgan, or the ability of x-rays to ionize air. Regardless of the method used, the basic elements of an

TABLE IV

A.E.C. Internal Compensation Networks

1. Kilovoltage compensation
2. Sensitivity of individual sensing areas in pickup device
3. Exposure rate compensation
4. Compression cone compensation
5. Overall density adjustments
6. Cassette size dependent blackening correction
7. Field size dependency compensation (e.g.,Four-on-one spot film format)
8. Leakage current compensation (Ionization type)
9. Dark current compensation (Phototube type)
10. Cable charge compensation (corrects for energy stored on capacitance of high tension cables)
11. Auxiliary device compensation (several auxilary devices with A.E.C pickups may be connected to the same electronic control circuit)
12. Turn-off delay (Compensates for differences in delay between relay-controlled x-ray apparatus and thyristor-controlled)
13. Detector selection compensator (One system may utilize both ionization type and phototube type of detectors, and compensation is required whenever the type of detector is switched)
14. Thickness of ionization chamber (For systems which are capable for accepting two or more chamber sizes)

TABLE V

A.E.C. External Compensation Networks

1. Density control
2. Screen sensitivity correction
3. Patient thickness compensation

A.E.C. system are the same (Figure 32).[11]

A pickup, located near the plane of the image receptor, either anterior or posterior to the cassette, samples radiation by absorbing a finite number of x-ray quanta which have passed through the patient. An electrical signal is produced which is proportional to the intensity of the radiation, and an electronic circuit then integrates this signal. When the film has received just enough radiation to produce the desired optical density, a signal is relayed to the generator and a switch is opened, terminating x-ray production. This is the standard textbook phototimer. In the real world, many physical problems must be overcome to al low the A.E.C. device to perform adequately, and the device must be properly calibrated.

DETECTORS

There are two types of sensor pickups used by the majority of equipment manufacturers to detect the transmitted radiation:

1. Scintillator Type

2. Ionization Type

In addition, most manufacturers use photomultiplier tube or photodiodoes for brightness control in cine radiography and photo-fluorographic cameras, such as the 105 mm or the 100 mm cameras. Sensing for automatic exposure rate control in fluoroscopy is either by photomultiplier tube, photodiode, or video sensing in the T.V. chain.

SCINTILLATOR TYPE

The pickup of the scintillator type device consists of a sheet of light-conducting plastic in contact with an x-ray sensitive phosphor, coupled to a photomultiplier tube, which creates an electrical signal proportional to the intensity of the light. This represents two stages of energy conversion: (1) radiation is changed into a light signal, and (2) the light signal is changed into an electrical signal.

Since the photopickup consists of a laminate of luminescent screen, paper and plastic, it is more rugged than the ionization chamber pickup. A single photomultiplier tube may be used along with mechanical shutters to control the light emitted from each of three scintillators in the pickup device. The three scintillators define three sensitive regions, fields or dominants in the plane of the pickup, and each field can usually be selected singly, or in combination. Alternatively, there may be a separate photomultiplier

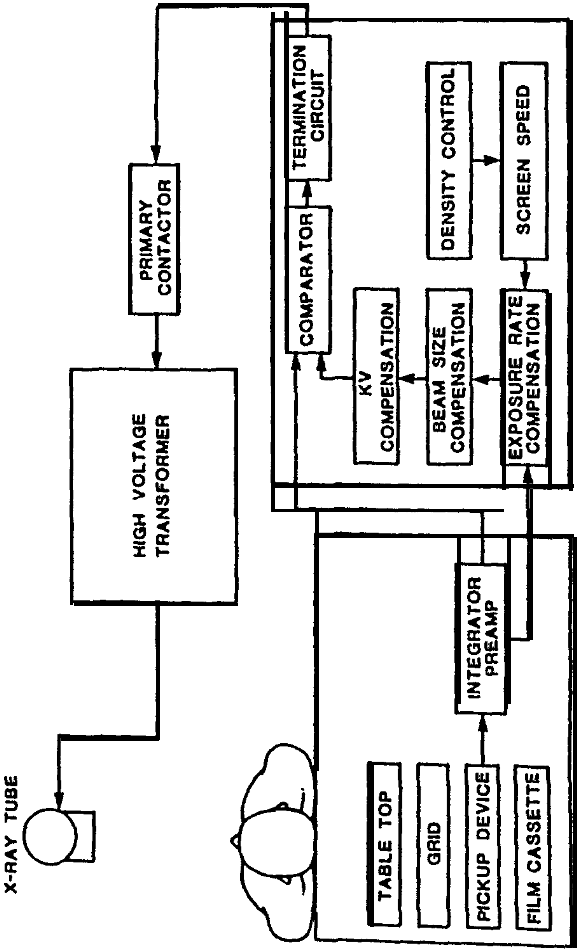


Figure 32. The basic components of an A.E.C. device.

IONIZITION TYPE

The ionization pickup consists of thin metal electrodes separated by air space. X-rays passing through this pickup produce free electrons, which are collected by the electrodes and produce a small electrical current. This current, which is usually in the nanoampere range, is proportional to the x-ray intensity. Compared to the scintillator, this represents only one stage of energy conversion: radiation is changed directly into an electrical signal.

Ion chambers, because of their low current generation, must have fixed lengths of cable, not exceeding 35 meters, to carry the signal. Some require a first stage pre-amp just outside the chamber to increase signal strength and lower impedance.

DETECTOR LOCATION

There are three possible locations for a detector, whether it be a scintillator or an ion chamber:[12, 13]

1. Between the table top and the grid.

2. Between the grid and the image receptor.

3. Posterior to the image receptor.

The first position is rarely used because it samples all radiation including scatter, whereas the image receptor receives radiation which has been considerably altered in spectral characteristics and intensity by the grid. If the detector is in position (3), on the exit side of the cassette, it is called a ‘posterior detector”. The x-rays which reach the posterior detector are of no further diagnostic value and can be absorbed by the detector with no added patient exposure. Because of the low amount of radiation which is available, after passing through the patient, the grid, the cassette, and the two intensifying screens, this method requires a highly sensitive detector.

Cassettes which are to be used with posterior detector A.E.C. systems must be of special construction and have little or no lead in the back portion of the cassette. A lead thickness of 0.0025(0.0635mm)“is maximum.

The radiation reaching the posterior pickup has a different spectral character due to the filtration of the image receptor. Radiation intensity is also less because of this absorption. Posterior detectors have proven to be a disadvantage since the introduction of rare earth screens, because these screens absorb more quanta than do the calcium tungstate screens, and the beam spectrum is altered considerably. However, one very sucessful application of posterior detectors has been for those imaging systems which do not use cassettes (i.e., automatic film loaders, such as the Picker Rapido™).

Since the A.E.C. device is used to control radiographic density, the detector should sample all of the radiation which contributes to that density. The logical place for the detector is, therefore, directly in front of the film, posterior to the grid. When the pickup is located between the grid and the cassette, it is called an “anterior detector”.

With the pickup located posterior to the grid, there should be no need to compensate for secondary radiation from the patient. This is true for the most part: however, secondary radiation is generally different in quality from the primary radiation, and originates in subject details which are widely distributed in space. In general the secondary radiation contribution varies according to the nature and the size of the object being radiographed, the field size, type of collimation and kV used. Thus, compensation for these effects may be required.

DETECTOR FIELDS

Most manufacturers provide three fields or sensitive regions within the pickup device. These are general by operator selectable, singly or in combination. To effectively measure the amount of radiation being delivered to the image receptor, the body part of interest should be positioned over the sensitive area of the detector. This diagnostic area of interest is referred to as the "dominant". The radiation passing through the dominant and impinging on the sensitive field causes the current which is used to terminate the exposure.

Both ionization type and scintillator type detectors may have three separate fields. In anterior pickups the detectors may be somewhat radiopaque, casting a shadow on the radiograph at low kV’s. This effect is more a function of manufacturing design than whether the detector is an ion chamber or a screen phosphor. Several manufacturers have successfully designed pickups with detectors which are only slightly visible even at 35 kV.

Whenever a phototimer is newly installed or if the pickup or electronics must be removed for service, it is important to verify that whenever a field is selected at the control desk, that corresponding field, and only that field, is energized at the pickup device. This is relatively simple to check and will relieve much frustration which may result if, for example, the upper left field is energized whenever the upper right field is selected, and vice-versa.

DESIRABLE FEATURES OF AN A.E.C. SYSTEM

A well designed automatic exposure control system should have the following characteristics:

1. It should properly terminate the x-ray exposure, providing the desired radiographic optical density for a variety of conditions. This consistency of performance is called tracking. A.E.C. systems should track under the following conditions:

   a. As tube potential is changed from 50 to 150 kVp.

   b. For variation6 in patient thickness.

   c. When cassette size is changed, or multiple format spot films are utilized.

2. The device should operate consistently, resulting in reproducible radiographic exposures.

3. The pickup shoul d not degrade the radiographic image by producing additional scatter radiation, nor by appreciably attenuating the x-ray beam so that the exposure must be increased.

4. The pickup should not appreciably increase patient film distance.

5. The pickup should be rugged and not influenced by external forces such as humidity, temperature, and atmospheric pressure.

6. The system should offer a variety of dominant field6 to select, as required.

7. The pickup must provide a uniform response regardless of the field or combination of fields selected.

8. The device should provide sufficient internal compensation adjustments to provide good tracking should the screen-film combination be changed.

9. It should provide sufficient operator controlled compensation adjustments.

10. It should not be used with a high kilowatt generator unless forced commutation, grid control, or secondary high tension switching is also provided.

11. It should include a backup termination system which will terminate the exposure in the event of A.E.C. system failure. This is necessary to preserve the x-ray tube and to avoid hazardous exposures to the patient.

A.E.C. PERFORMANCE EVALUATION

A large number of test methods have appeared in the literature.[14-18] These range from direct measurement of a system parameter (e.g., minimum exposure time) to indirect evaluation of performance (e.g., inverse square law verification). The exact testing protocol is a matter of personal preference but should consist of procedures which can be correlated with the clinical functioning of the system. In general, the following should be considered before evaluating performance of an A.E.C.

1. Make radiographic exposures through a suitable attenuator and measure the resultant optical densities- a phototimer is intended to provide consistent film density, which is not necessarily synonymous with constant radiation exposure.[19]

2. Choose a suitable attenuator and be consistent. Water or acrylic is recommended. Masonite (pressed wood) does not produce a uniform radiographic density, which makes interpretation of results difficult. Aluminum and copper are poor choices since their attenuation and scatterin properties differ greatly from those of water (tissue)[20] and the thickness corresponding to a given amount of tissue is highly dependent upon the kV.

3. In a new installation, provide the vendor with your test methods and criteria.

4. Verify the reciprocation, centering, and alignment of the grid. Do not use source to image receptor distance which exceeds the operating range of the grid.

5. If adjustment of the internal compensation circuitry is necessary, use the same cassette for all exposures and monitor the processing closely. This will assure that changes in radiographic density are only due to the internal adjustments.

6. If more than one film-screen combination is to be used, verify that the provided compensation adjustments are adequate to assure acceptable tracking for each image receptor.

Record photomultiplier high voltage, or comparator reference voltage, as a function of kV selected, as a function of density or patient compensation controls.

This will serve as a baseline if compensation adjustments are required or to confirm a suspected drift in sensitivity.

8. Record the change in optical density as a function of photocell high voltage, or comparator reference voltage. This will help to establish the setting required for the specified optical density.

FLUOROSCOPY

The purpose of automatic exposure control in fluoroscopy is to maintain a constant luminance at the output phosphor of the image intensifier by controlling one or more technical factors. The image brightness can be monitored directly via a mirror or prism (Figure 33),[15], via the photocathode current of the image intensifier, or the video signal of the television pickup tube. The technical factor(s) controlled depends upon the design or mode of operation. The commonly used modes are given in Table VI.

EXPOSURE RATE SETTINGS

Regardless of the method used, the fluoroscopic exposure rate at the image conversion plane (i.e., at the input phosphor of the image intensifier) should remain constant over a range of attenuator thicknesses which correspond to kV values between 70 kVp and 90 kV.[23] Above or below these values, the input exposure rate will increase as the sensitivity of the input phosphor decreases or absorption in glass (metal) entrance window increases. Typical values of input exposure rate range from 20 to 100 uR/sec (1.2 to 6.0 mR/min) for a 9-inch diameter image tube. The actual value depends upon the system design and acceptable noise limits, but typically is not greater than 60 uR/sec (3.6 mR/min). For magnified image mode, these values will increase by a factor which is approximately the square of the ratio of the image diameters. The integral dose, however, is generally less for magnified modes, especially for kV variable brightness stabilizers. In general, an increase in radiation exposure rate is not an acceptable substitute for poorly designed or poorly adjusted imaging systems. The light quanta available at the television pickup tube is a function not only of radiation exposure, but also screen efficiency, intensifier gain, intensifier focus, quality of optics, and aperture size. For a given exposure rate, the intensifier aperture, pickup tube and video display must be adjusted for optimum signal-to-noise in the final image.

For serial floorographic cameras (70 mm and 105 mm roll film or 100 mm cut film) or for cinefluorographic cameras, the required exposure per frame is highly

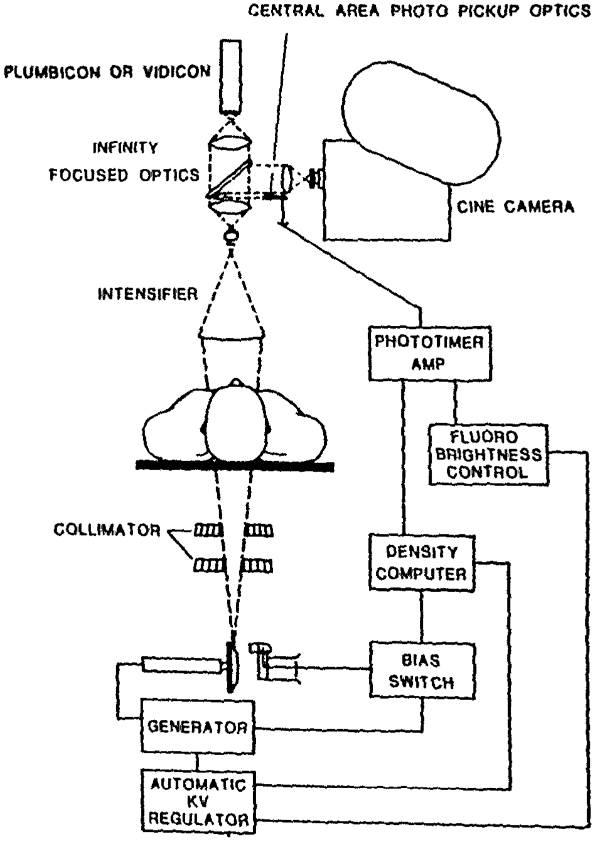


Figure 33. Automatic brightness control for fluoroscopic and fluorographic recording of the x-ray image.

TABLE VI

Variations in Automatic Brightness Control Mechanisms

1. Operator controlled kV, brightness controlled mA.
2. Operator controlled mA, brightness controlled kV.
3. Brightness controlled mA with kV override.
4. Brightness controlled kV and mA, with both increasing or decreasing together.
5. Brightness controlled pulse width.
6. Pulse width controlled with kV override.

dependent upon the imaging system, film type, processing, aperture setting, and noise level which can be tolerated. In general, the required exposure can be minimized only by a concerted effort to optimize each of these parameters. The typical values of image intensifier input exposure are 0.05 to 0.20 mR/frame for serial fluorographic camera and 0.01 to 0.04 ml/frame for cinefluorographic cameras.24 Emphasis should be placed on setting the minimum exposure, consistent with the clinical needs of the system.

SYSTEM RESPONSE TIME

The ability of the automatic brightness control system to quickly respond to changes in x-ray attenuation is important. This is especially true for kV-variable systems which always start at a low kV value. If these systems do not respond quickly to raise the kV to the required value, the radiologist will soon be dissuaded from using intermittent fluoroscopy. It is, therefore important to measure the time required for the kV to drive from the exposure off value (or the value corresponding to an attenuator thickness of 0.5" aluminum), to the value corresponding to an attenuator thickness of 2.5" to 3" of aluminum. The time required for the system to reach at least901 of the stablizied kV value should be less than 0.5 second.

MAXIMUM PATIENT ENTRANCE EXPOSURE RATE

The patient entrance exposure rate should be checked to verify that the maximum specified limits are not exceeded. These limits[25]are 5 R/min for units without automatic exposure rate control and 10 R/min for units with automatic exposure rate control. Units equipped with an optional high level control can exeed these limits.

SUMMARY

Automatic Exposure Control has been used in roentgenography for over 30 years. However, successful application of this device requires a thorough understanding of not just the purpose, but also the function of a A.E.C. device. Both scintillator and ionization pickups are widely used, but regardless of the type of detector, adequate compensation networks must be incorporated if the device is to perform satisfactorily. The A.E.C. device must also be calibrated by qualified service personnel using the same film-screen combination and processing conditions as used clinically. Most pickups are located between the grid and the image receptor, and offer a choice of three fields or dominants. It is important to verify that the field selected at the control is in fact the one energized at the pickups.

The A.E.C. device should track well as the tube potential, patient thickness, and field size are changed. In addition, it must provide reproducible exposures.

REFERENCES

1. “A Calibration System for X-Ray Generators and Tube Factors”, T. Healey, et al, British Journal of Radiology, Vol. 52, pp 44-50,1979.

2. “Selection of Technique Factors for Mobile Capacitor Energy Storage X-Ray Equipment”, K.W. Weaver, et al, Radiology, Vol. 128, Nr. 1, pp 223-228, 1978.

3. “Principles of Diagnostic X-ray Apparatus”, D.R. Hill (Editor), Philip6 Technical Library, pp 162 & 340, 1975.

4. “Effects of Roentgen Tube Voltage and Current Waveforms in Radiography’“. 11. Kanamori, Acta Radiological (Therapy), Vol. 4, pp 68-80, 1966.

5. “The Principle of Falling Load”, C.H. Levsen, Medicamundi, Vol. 14, Nr. 1, 1969.

6. “Performance Evaluation of the Falling Load Techniques”, P.L. Rauch and R. Block, SPIE, Vol. 127, pp 145-151, 1977.

7. ‘Acceptance Testing Experience with Fourteen New Installations," P.L. Rauch and R. Block, SPIE, Vol. 196, pp 12-18, 1976.

8. “Performance Specifications and Technical Pitfalls in the Equipment Purchase of Radiological Imaging Devices”, P. P. Lin, in Radiological Equipment Systems Management, Monograph No. 1, Society for Radiological Engineering Seminar, Marina Del Rey, California, June 3-5, 1981.

9. "A Photoelectric Timing Mechanism for the Automatic Control of Roentgenographic Exposure”, R. H. Morgan, American Journal of Roengenography, Vol. 48, pp 220-228, 1942.

10. “The Trail of the Invisible Light”, E.R.N. Grigg, pp 145 and 415, Charles C. Thomas, Publisher, 1965.

11. “X-ray Automatic Exposure Timing and Control Circuitry”, E. S. Joseph and J. E. Schnieble, SPIE, Vol. 70, pp 166-170, 1975.

12. "X-ray Automatic Exposure Control", G. P. Standhope, SPIE, Vol. 70, pp 171-175, 1975.

13. "A Different Phototimer Placement in Automated Exposure Control", J. C. Hoeffel, et al, Radiologic Technology, Vol. 43, pp 347-349, 1972.

14. "Field Evaluation of Radiographic Phototimers", W. R. Hendee, et al, SPIE, Vol. 70, pp 183-188, 1975.

15. "Characteristics and Evaluation of Automatic Exposure Controls". J. R. Craig, SPIE, Vol. 70, pp 189-195, 1975.

16. "Phototimers, User's Point of View", P.J.P. Lin, SPIE, Vol. 70, pp 196-200, 1975.

17. "Automatic Exposure Control in General Radiography", A. D. Smythe, Investigative Radiology, Vol. 10, pp 259-266, 1966.

18. "Test Methods for Diagnostic X-ray Machines for Use During Initial Installation", NEMA Standards Publication No. XR8-1979, 1979.

19. "Performance Evaluation of Automatic Exposure Control Systems", B. A. Horn and M. G. Randall, 20th Annual Meeting of the American Association of Physicists in Medicine, July 1978.

20. "System Level Performance Testing of Image Intensified X-ray Equipment", J. A. Mulvaney, et al, SPIE, Vol. 273, pp 153-160, 1981.

21. "Attenuation Phantoms for Patient Exposure Measurement During Radiographic Examinations Utilizing Phototiming Techniques", P-J. P. Lin, NBS SP456, pp 381-388, 1976.

22. "Variation of X-ray Tube Potential as a Function of Attenuator Thickness in kVp Variable Automatic Brightness Stablization Fluoroscopy", P-J. P. Lin, and R. Kriz, SPIE, Vol 127, pp 152-157, 1977.

23. "Cameras for Image Intensifier Fluorography", ICRU Report 15, 1969.

14. "Regulations for the Administration and Enforcement of the Radiation Control for Health and Safety Act of 1968", HHS Publication (FDA)80-8035, 1980.

Part 2

CHARACTERISTICS AND PERFORMANCE SPECIFICATIONS FOR X-RAY GENERATORS AND AUTOMATIC EXPOSURE CONTROL DEVICES

This section of the report contains generalized definitions, operational characteristics and parameters for which performance specifications might be developed for x-ray generator6 and automatic exposure control devices. When evaluating different radiological imaging systems it is useful to have each potential vendor supply such information as it relates to a specific system. The majority of this information is typically available in the product data sheets provided by the vendor and maybe obtained by review of these data sheets. Alternately a series of forms may be prepared to be provided to the vendors to have them "fill in the blanks" for the relevant information desired. Eigher approach is acceptable. Please note, however, that the anticipated levels of performance specified in Section Three of this report are higher than the levels typically found on vendor's product data sheets or may not be specified at all by the vendor. Therefore, a series of "fill in the blanks" tables for vendors to complete regarding performance considerations helps to insure that performance levels not found on product data sheets are specified in writing during the bidding process. Anticipated and acceptable levels of performance are identified in Part 3.

X-RAY GENERATORS

DEFINITION

An x-ray generator is taken to mean those components of a radiological imaging system required to supply and or distribute electrical power to the remaining elements of the system and to control the radiologic technique factors. As an example, an x-ray generator might normally include a power unit/electronics module: a high voltage transformer/rectifier and/or control module, an operators control module: a x-ray tube rotor control module and high voltage cables. It therefore includes all components required to operate and control an x-ray tube(s), beginning at the electrical connection to the primary power supply and ending with the high voltage cables connected at the x-ray tube. However, since the performance characteristics of the x-ray generator cannot be evaluated unless connected to an x-ray tube, certain aspects of the performance of the x-ray tube in con-Junction with the x-ray generator will be considered as well. Characteristics and parameters for consideration would include the following:

POWER REQUIREMENTS

1. Number of voltage sources required.

2. Voltage type, phase, range, kVA rating, circuit breaker requirements, maximum line resistance, maximum line current and recommended wire gauge for each voltage source and number of wire connections required for three phase systems.

3. Required line voltage regulation (at full load) and tolerance to voltage surges, sags and impulses for each voltage source.

4. Acceptable voltage supply configuration for three phase (wye versus delta wiring configuration).

5. Possibility of simultaneous biplane operations from same power line.

CONTROL CIRCUITRY/HIGH VOLTAGE TRANSFORMER/ SERVICE ADJUSTMENTS

1. High voltage transformer primary and secondary voltage range, type and number of rectifier-e employed and type of high voltage waveform.

2. Secondary current range and type of secondary current waveform.

3. X-ray generator kW rating and maximum mA rating at 60, 80, 100, 125 and 150 kVp.

4. Presence of generator overload detection circuitry and phase loss detection circuitry.

5. Generator duty cycle for all modes of operation.

6. Secondary voltage regulation.

7. Secondary voltage ripple as a function of tube current and kilovoltage.

8. Number of controllable x-ray tubes.

9. Number of filament transformers for small and large focal spots.

10. Type of high voltage switching.

11. Provisions of service adjustment of standby filament current, for delay time for anode rotation/filament boost, for kVp compensation, for space change compensation, and for mA stabilization for each tube and focal spot.

12. Number of steps, duration of steps and percentage of maximum load for stepped falling load systems.

13. Percentage of maximum load to which continuously falling load systems are adjusted.

14. Provision for prevention of magnetic core saturation.

15. Type of high voltage cable and end termination and maximum recommended cable length.

16. Type of exposure contacting.

17. Exposure initiation and termination time.

OPERATORS CONTROL

1. Independently selectable technique factors for non-automatically and automatically control led exposures.

2. Number of selectable x-ray tubes and location(s) of selected tube indication.

3. Method of technique parameter display/indication.

4. kV, mA, mAs, time range and increment for

radiography and fluoroscopy.

5. Applicability of generator to mammography/tomography and restrictions.

6. Type of line voltage compensation.

7. Presence of "non-bucky" mode.

8. Listing of all parameters indicated at operators control.

9. Type of tube protection circuitry available.

10. Method of selecting anode rotational speed.

11. Limits of tube protection circuitry.

12. Availability of exposure counters.

COMPONENT CHARACTERISTICS

1. Height, width, depth

2. Weight

3. Heat Dissipation

PERFORMANCE CONSIDERATIONS

1. Exposure timer error for $t < 5$ msec, 5 msec $< t <$ 20 msec, and $t > 20$ msec and timer reproducibility.

2. kV error @ 10, 50, 100, 500 and 1000 msec.

3. Maximum kV overshoot associated with exposure initiation.

4. kV symmetry(anode to ground and cathode to ground).

5. kV reproducibility.

6. kV time independence.

7. mA or mAs error at 50, 100, 500 and 1000 msec.

8. Maximum mA overshoots associated with exposure initiation.

9. mA or mAs reproducibility.

10. mA time independence.

11. Percent loading of tube on falling load generators.

12. Overrate/underrate error of tube protector.

13. Exposure output in mR/mAs @ 80 kVp at a given distance.

14. Exposure reproducibility.

15. Exposure linearity between adjacent mA or mAs stations and over entire range of mA or mAs stations.

16. Beam quality at 68, 90 and 120 kVp.

AUTOMATIC EXPOSURE CONTROL DEVICES

DEFINITION

An automatic exposure control device is taken to mean any sensing device which produces an electrical signal in response to the interaction of x-ray radiation within the device which is subsequently processed to control the exposure termination so as to yield consistent optical densities of radiographic images over a broad range of technique and patient variables. It may normally consist of one or more sensors, an electronic control module and an operators module.

AUTOMATIC EXPOSURE CONTROL DEVICE CHARACTERISTICS

1. Type of automatic exposure control sensor.

2. Location of automatic exposure control sensor.

3. Number of automatic exposure control sensor fields which can be independently selected and selected in combination.

4. Geometry of automatic exposure control sensing fields.

5. Field size restriction for single sensing field only.

6. Sensing field size in plane of image receptor or percentage of image field sampled.

7. Range of density control selector.

8. Number of image receptors of different sensitivities which can be accomodated.

9. Method of establishing maximum allowed automatically controlled exposure duration.

10. Provision for kV compensation for multiple image receptor6 and whether circuit is fixed or adjustable.

11. Availability of anticipation circuitry.

12. Common or independent processing electronics.

13. Field size compensation provided.

14. Sensitivity matching of allowed fields.

AUTOMATIC EXPOSURE CONTROL DEVICE
PERFORMANCE CONSIDERATIONS

1. Sensitivity matching of independently selectable fields or field combinations.

2. Reproducibility of automatically controlled exposures.

3. Minimum automatically controlled exposure duration.

4. Maximum variation in film optical density due to field size variation.

5. Range of exposure variation provided by density control.

6. Maximum variation in film optical density as a function of kV and attenuator thickness.

7. Maximum allowed exposure duration in kWs or mAs.

Part 3

TEST METHODS AN PERFORMANCE LEVELS FOR X-RAY GENERATORS AND AUTOMATIC EXPOSURE CONTROL DEVICES

This section of the report outlines detailed test methods for evaluating the performance of x-ray generators and automatic exposure control devices incorporated as part of a clinically installed radiological imaging system. Anticipated levels of performance are given which should be applicable to systems which have been properly installed and calibrated by the vendor. The test methods and performance levels provide here are not unique. Rather, they are based on extensive experience in the evaluation of clinically installed radiological imaging systems of many different vendors and have proven to provide reliable results.

TUBE PROTECTION CIRCUITRY

TEST METHOD

The x-ray tube protection circuit of the x-ray generator shall be evaluated by comparison of the indicated techniques at which the circuit first inhibits the initiation of a single radiographic exposure to the techniques at which exposure should be first inhibited as determined from single exposure radiographic rating charts for each x-ray tube/focal spot controlled by the x-ray generator.

PERFORMANCE LEVEL

1. The x-ray tube protection circuit shall inhibit the initiation of any exposure in excess of 100% of the maximum allowable exposure as determined from the single exposure exposure radiographic rating charts.

2. The x-ray tube protection circuit shall not inhibit the initiation of any exposures which are less than the following specified percentages of the maximum allowable exposure as determined from the single exposure radiographic rating charts:

a.	Single x-ray tube:	85%
b.	Multiple x-ray tubes of similar filament and thermal characteristics:	75%
C.	Multiple x-ray tubes of dissimilar filament and thermal characteristics:	65%

This performance level is applicable to all tubes connected to the x-ray generator.

EXPOSURE TIME

TEST METHOD

Exposure time shall be measured by means of a calibrated high voltage divider and storage oscilloscope or a Machlett Dynalyzer TM system. Measurement6 will be made at an indicated peak tube potential (kV) of 80 and a tube current (mA) sufficient to minimize the influence of starting steps is taken or stored secondary charge on the decay of the high voltage waveform (e.g., 300 to 400 mA). For mammagraphic equipment, Measurements shall be made at 30 kVp and the maximum allowed mA for the large focal spot at this kVp. For single phase equipment, exposure time is taken to be equal to the numver of pulses times 8.33 milliseconds (msec). For three phase equipment the exposure time is taken to be equal to the time from threshold crossing of the leading edge of the kVp waveform to threshold crossing of the trailing edge of the kVp waveform, where the threshold is specified by the manufacture as a percentage of peak tube potential (e.g., 75% - 80%).

PERFORMANCE LEVEL

1. Exposure time error:

For $t_i < 5$ msec:

$$\{(t_m - t_i)/t_i\} < + .15$$

or

$$(t_m - t_i) < + 1 \text{ msec}$$

For 5 msec $< t_i <$ 20 msec:

$$\{(t_m - t_i)/t_i\} < + .10$$

For $t_i >$ 20 msec:

$$\{(t_m - t_i)/t_i\} < + .05$$

2. Exposure time reproducibility:

$$\{(s_{tm})/\langle t_m\rangle\} < + .05$$

where: t_i is the indicated exposure time

t_m is the measured exposure time

$\langle t_m\rangle$ is the average value of the measured exposure time for N replicate measuremtns where $3 < N < 10$

^{s}tm is the estimated standard deviation associated with <t>.

This performance level is applicable to any form of exposure time indication/display regardless of whether it is operator selected or not.

TUBE POTENTIAL

TEST METHOD

Tube potential (kV) shall be measured by means of a calibrated high voltage divider and storage oscilloscope or a Machlett Dynalyzer™ system. The high voltage divider may be inserted at the x-ray tube or the high voltage transformer. Any loading effects associated with the high voltage divider/jumper cables will be determined and corrected for. Consistent with the ratings of x-ray tube and generator, measurements will be made at each available tube current (mA) station for constant load systems or for each available focal spot load for falling load systems. Measurements will be made over the rated range of the generator (nominally 50 to 150 kV) in 10 to 20 kV increments except for dedicated mammographic systems in which case kVp increments will be smaller. Measurements may be made for nominal exposure times of between 10 and 500 milliseconds (msec) with the most typical value being 100 msec. In the event that direct measurement of the high voltage applied to the x-ray tube is not possible, a non-invasive kVp measuring instrument, which has been calibrated to a high voltage divider, may be used in lieu of the high voltage divider system.

PFRFORMANCE LEVEL

1. kV error:

$$\{(kV_m - kV_i)/kV_i\} < + .05$$

2. kV reproducibility:

$$\{s_{kVm}/\langle kV_m\rangle\} < + .05$$

3. kV symmetry:

$$(kV^A{}_m - kV^C{}_m) < + 2\ kVp$$

4. kV time independence:

$$\{(kV^{t1}{}_m - kV^{t2}{}_m)/(kV^{t2}{}_m + kV^{t2}{}_m)\} < .03$$

here: kV_i is the indicated kV

kV_m is the measured kV

$\langle kV_m\rangle$ is the average value of the measured kV for N replicate measurements where $3 < N < 10$

s_{kVm} is the estimated standard deviation associated with kVp_m

kV^{A}_{m} is the measured anode kV

kV^{C}_{m} is the measured cathode kV

kV^{t1}_{m}, kVp^{t2} are the measured kV's for any given exposure at times t_1 and t_2 respectively from the start of exposure where 10 msec $< t_1 < 50$ msec, 50 msec $< t_2 < 500$ msec.

The tube potential waveform is expected to exhibit equal amplitude pulses and freedom from overshoots, dips, ramps, spikes and other unusual or abnormal changes from the nominal kilovoltage.

If tube potential overshoots associated with the initiation of exposure (including falling load steps) exist, they shall not exceed the indicated kV by more than 5 kV or 5% of the indicated kV, which ever is smaller.

This performance level is applicable for all x-ray tubes connected to the x-ray generator and all operational modes.

TUBE CURRENT

TEST METHOD

Tube current (mA) during radiographic operation shall be measured by one of two means: 1) by means of a 10 ohm, 1%, 50 watt resistor inserted in series with the ground return of the x-ray generator mid-secondary (or equivalent location in the circuit): the voltage drop across the resistor will be measured with a calibrated Oscilliscope: 2) by means of the Machlett Dynalyzer™ system. Perturbations, if any, associated with the insertion impedance of a cathode jumper cable will be determined and corrected for. Measurements will be made at each available tube current (mA) station for constant load systems or at each available focal spot load for falling load systems and over the rated tube potential (kV) range of the x-ray generator consistent with both x-ray tube and x-ray generator ratings. Measurements may be made for nominal exposure times of between 10 and 500 milliseconds (msec) with the most typical value being 100 msec. During fluoroscopic operation tube current will be measured by means of a digital DC mA meter inserted in series at the same location as the 10 ohm resistor.

PERFORMANCE LEVEL

1. mA error:

$$[(mA_m - mA_i)/mA_i] < + .05$$

2. mA reproducibility:

$$[s_{mAm}/\langle mA_m \rangle] < + .05$$

3. mA time independence:

$$(mA^{t1}{}_m - mA^{t2}{}_m)/(mA^{t1} + mA^{t2}{}_m < .05$$

where: mA_i is the indicated mA

mA_m is the measured mA

$\langle mA_m \rangle$ is the average value of the measured mA for N replicate measurements where $3 < N < 10$

s_{mAm} is the estimated standard deviation associated with $\langle mA_m \rangle$

$mA^{t1}{}_m$, $mA^{t2}{}_m$ are the measured mA's for any given exposure at times t_1 and t_2 respectively from the start of exposure where 10 msec < t_1 < 50 msec, 50 msec < t_2 < 500 msec

Initial mA overshoots exclusive of those due to cable charging shall not exceed 10% of the measured mA.

For falling load x-ray generators with stepped constant load, the mA during the first step shall be adjusted to not less than 85% of the maximum x-ray tube loading, but not more than 100% of the allowable load. The product of kVp times mA during the first step shall remain constant for all kVp settings, except where the mA would require more than the maximum allowable filament current. The mA during subsequent steps shall be adjusted to the percentage of the maximum mA allowed during the first step as specified by the manufacturer.

For falling load x-ray generators with continuously falling load, the initial mA shall be adjusted to not less than 05% of the maximum mA allowed for a 10 millisecond (msec) exposure, but not more than 100% of the allowable load. The product of kVp times intial mA shall be constant for all kVp settings, except where the mA would require more than the maximum allowable filament current. The falling load curve shall be adjusted to provide the same percentage of maximum x-ray tube load for all mAs settings.

The performance level is applicable to all x-ray tubes connected to the x-ray generator and all operation modes,

mAs TIMER

TEST METHOD

For those x-ray generators which do not provide independent control of tube current (mA) and exposure time, but only their product (milliampere-seconds(mAs)), mAs shall be measured by means of a digital electronic integrating coulomb meter (mAs meter) inserted in series with the mAs metering circuit. Measurements will be made over the rated range of the x-ray generator consistent with x-ray generator and x-ray tube ratings.

PERFORMANCE LEVEL

1. mAs error:

$$\{(mAs_m - mAs_i)/mAs_i\} \leq .05$$

2. mAs reproducibility:

$$\{s_{mAsm}/\langle mAs_m\rangle\} \leq .05$$

where: mAs_i is the indicated mAs

mAs_m is the measured mAs

$\langle mAs_m\rangle$is the average valueof the measuredmAs for Nreplicate measurements where $3 \leq N \leq 10$

$s_{mAsm}$is the estimate standard deviation associated with $\langle mAs_m\rangle$

The performance level is applicable to all x-ray tubes connected to the x-ray generator and all operation modes.

EXPOSURE OUTPUT, REPRODUCIBILITY OF EXPOSURE OUTPUT, LINEARITY OF EXPOSURE OUTPUT AND BEAM QUALITY

TEST METHOD

For purpose of the following test it is assumed that a source assembly (x-ray tube and beam restriction device) of the same manufacture as the x-ray generator has been installed and calibrated in conjunction with the x-ray generator.

The radiation quantity and quality characteristics of the source assembly and x-ray generator combination shall be measured under conditions of good geometry by means of an ionization chamber/dosimetry system having a suitable energy response over the diagnostic energy range (20 keV to 150 keV effective) and having a collection efficiency of better than 95% at the maximum beam intensity to be encountered. The range of tube potential (kv), tube current (mA), and exposure times used for exposure measurements will be consistent with the ratings of each focal spot of the source assembly/x-ray generator combination. The ionization chamber will be located between 60 and 100 centimeters from the x-ray tube focal spot. Beam quality will be determined by measurement of the attenuation curve using Type 1100 aluminum attenuators. In making exposure measurements, except for the determination of beam quality, each independently controlled technique factor will be altered and reset between exposures.

PERFORMANCE LEVEL

1. Exposure Output: For an indicated kV of 80, at a distance d centimeters from the source the exposure output measured free-in-air per indicated milliampere second shall be between $15(61/d)^2$ and $25(61/d)^2$ milliroentgen (mR) per indicated milliampere seconds (mAs) for three phase, six or twelve pulse, constant potential and frequency invertor x-ray generators and between $10(61/d)^2$ and $18\ (61/d)^2$ mR/mAs for single phase full wave rectified x-ray generators.

2. Exposure reproducibility:

$$\{s_{X_m}/\langle X_m\rangle\} < .05$$

where: $\langle X_m\rangle$ is the average exposure in millioroentgen(mR) for Nreplicate measurement where $3 < N < 10$

s_{X_m} is the estimated standard deviation associated with $\langle X_m\rangle$

3. Exposure linearity (fixed indicated kVp)

a. Between adjacent mA/mAs stations

$$\frac{[(\langle X_m\rangle/mAs_i)^j - (\langle X_m\rangle/mAs_i)^k]}{[(\langle X_m\rangle/mAs_i)^j - (\langle X_m\rangle/mAs_i)^k} < 0.05$$

Where $(\langle X_m\rangle/mAs_i)^j$ is the average measured exposure (mR) per indicated mAs at the jth mA or mAs station at a given indicated kVp.

$(\langle X_m\rangle/mAs_i)^k$ is the average measured exposure (mR) per indicated mAs at the kth mA or mAs station at a given indicated kVp and the jth and kth mA or mAs stations differ from each other by no greater than a factor of two.

b. Between all mA or mAs stations:

$$\frac{[(\langle X_m\rangle/mAs_i)^{max} - (\langle X_m\rangle/mAs_i)^{min}]}{[(\langle X_m\rangle/mAs_i)^{max} + (\langle X_m\rangle/mAs_i)^{min}]} < 0.10$$

where: $(\langle X_m\rangle/mAs_i)^{max}$ is the maximum measured exposure (mR) per indicated mAs for all mA or mAs stations at a given kVp

$(\langle X_m\rangle/mAs_i)^{min}$ is the minimum measured exposure (mR) per indicated mAs for all mA or mAs stations at a given kVp.

4. Ream Quality: The measured beam quality (half value layer in millimeters of aluminum) shall be greater than that specified by Title 21, CFR, Part 1020.30 mm but shall not exceed these values by greater than 50%.

The performance level is applicable to all tubes connected to the x-ray generator and all operational modes.

AUTOMATIC EXPOSURE CONTROL (AEC) SYSTEMS

GENERAL CONSIDERATIONS

The test methods describe herein shall be applicable to all automatic exposure control devices (e.g., table, wall board, photospot, cine, etc.) which are part of the clincally installed radiological imaging system. As the purpose of an automatic exposure control device is to provide consistent and reproducible optical densities over a wide range of imaging technqiues and patient variables, the test methods are designed to identify the range over which this function is accomplished as well as ranges in which this function is not accomplished. In evaluating the performance of any AEC device the following general considerations shall apply.

1. The attenuation medium herein referred to as the attenuator shall be either, (1) tap water contained in an acrylic tank, (2) homogeneous acrylic sheets, or (3) homogeneous tissue equivalent material (i.e., “solid-water”). The attenuator thickness shall be variable (nominally 5 to 30 centimeters in 5 cm increments) and its linear measurements shall be at least 35 cm by 35 cm. The attenuator will be located at the same position as would be occupied by a patient in the clinical system.

2. All measurements will be with the system set to the SID (source to image receptor distance) which represents the most common clinical configuration for the system.

3. The field size shall be smaller than the size of the attenuator but shall be equal to the size of the image receptor (or selected portion thereof) in the plane of the image receptor. For AEC systems utilized with film/screen combinations the typical field size employed will be 28 cm by 35 cm.

4. The image receptor employed (film, film/screen) shall be of the type to be utilized with the systemclinically. The film utilized in the testing shall be of the same emulsion number. For film/screen AEC systems, testing shall utilize the same cassette/screens for all measurements or multiple cassette/screens which have been verified to be matched in sensitivity to within +3%.

5. All test images shall be processed in the same processor. The processor wi11 be monitored sensitometrically at the beginning and end of each sequence of test images to determine the influence (if any) of processor variation on the test data.

6. Measurement of test image optical density shall be

made in a region centered to that area of the image which corresponds to the center of the AEC sensing element employed, using an internally referenced densitometer.

7. In addition to the optical density the following parameters may be measured during the evaluation of a given AEC device: (1) Exposure duration: (2) mAs, (3) kV; (4) AEC reference voltage: (5) AEC sensor output voltage; (6) pre-attenuator exposure: (7) post grid/pre-cassette exposure. In the case of exposure duration measurements by non-invasive means or in the case of exposure measurements the location of the measuring device shall be fixed in such manner as to not adversely influence the data acquired during testing.

8. It is assumed that the vendor has verified the proper reciprocation and centering with respect to the image receptor for any grid employed with the AEC device(s): has adjusted and calibrated the AEC device(s) to provide a gross optical density of between 1.2 and 1.4 for the image receptor/processing combination to be employed clinically; has adjusted and calibrated the AEC device(s) for optimum kVp compensation and verified the proper function of all internal and external compensation system. It is also assumed that the proper calibration of the x-ray generator has been verified.

9. AEC systems which provide for the independent selection of more than one image receptor type are expected to provide the specified performance levels for each image receptor type.

10. All tests will be performed at the “Normal” density control position and using the central AEC field (sense area) unless otherwise specified.

CORRESPONDENCE OF SELECTED FIELDS (SENSE AREAS) To ACTIVATED FIELDS (SENSE AREAS)

TEST METHOD

The correspondence of the AEC field(s) (sense area(s)) selected at the operators console to the AEC field(s) (sense area(s)) which is (are) activated in the plane of the AEC detector shall be determined by blocking all field(s) (sens area(s)) other than that selected at the operators control with a 6 millimeter (mm) thick lead sheet of dimensions slightly greater than the field(s) (sense area(s)) and initiating an automatically controlled exposure. The test is repeated with each field(s) (sense area(s)) being the only one unblocked by lead. No attenuator other than the lead sheet(s) will be in the useful beam and a low tube potential (kVp) (e.g., 50 kV) will be used.

PFRFORMANCE LEVEL

Correspondence of the AEC field(s) (sense area(s)) selected at the operators control to that activated in the plane of the AEC detector shall be demonstrated by normal (short) termination of exposure when all but the selected field(s) (sensor area(s)) are blocked by lead and by maximum (AEC limit) exposure when selected field(s) are blocked by lead, i.e., the AEC field(s) selected at the operators console must energize the corresponding field(s) at the AEC detector and only that (those) field(s).

VISUAL DELINEATION OF FIELD(S) (SENSE AREA(S))

TEST METHOD

Correspondence of the visual delineation of the AEC field(s) to the actual location of the AEC field(s) shall be determined by outlining the field(s) as visually delineated by the equipment with thin wire solder. A radiograph with no attenuator present will be obtained at an imaging technique which demonstrates the actual AEC field(s) and the visually delineated AEC field(s).

PERFORMANCE LEVEL

Displacement between the visually delineated AEC field(s) and actual AEC field(s) (sense area(s)) shall not exceed 7 millimeters in any direction.

MINIMUM CONTROLLABLE EXPOSURE DURATION

TEST METHOD

The minimum controllable exposure duration (under automatic exposure control) shall be determined from an analysis of high voltage waveforms and measured milliampere-seconds (mAs) under the following conditions. At 60 kV nominal, large focus and a tube load of 80% to 90% of the maximum, the attenuator thickness shall be adjusted to yield an exposure time or mAs of 25 milliseconds (msec) or 10 mAs or greater under automatic exposure control. The kV (nominal) will be subsequently increased in 10 kVp increments and automatically control led exposure made. For each exposure the width of the high voltage pulse at 75% of peak and the mAs shall be recorded. The minimum controllable exposure duration will be deemed to correspond to those values which are obtained when a subsequent increase in kV results in no further reduction in exposure time or mAs, and for which themeasured kV reaches a minimumof 90% of the indicated value.

PFRFORMANCE LEVEL

The minimum controllable exposure shall be less than or equal to 3 milliseconds or 3 mAs except for single phase, full wave rectified equipment for which the minimum controllable exposure time shall be no greater than 8.33 msec.

REPRODUCIBILITY

TEST METHOD

Reproducibility of automatically controlled exposures will be determined from the analysis of multiple test images or exposure measurements obtained at a fixed KV, attenuator thichness and tube load such that the exposure duration is greater than twice the minimum controlled exposure duration.

PERFORMANCE LEVEL

$$(s_{OD}/\langle OD\rangle) < .05$$

or

$$(s_X/\langle X\rangle) < .05$$

where $\langle OD\rangle$, $\langle X\rangle$ are the average values of test image optical density or exposure respectively for N replicate measurements where $3 < N < 5$.

s_{OD}, s_X are the estimated standard deviations associated with $\langle OD\rangle$, $\langle X\rangle$ respectively.

FIELD(S) (SENSE AREA(S)) SENSITIVITY MATCHING

TEST METHOD

Sensitivity matching of the AEC field(s) (retain sense area(s)) and combinations thereof will be determined from the analysis of multiple test images or exposure measurements for each field (sense area) and combination of fields at a fixed kV, attenuator thickness and tube load such that the duration of exposure is greater than twice the minimum controllable exposure duration.

PERFORMANCE LEVEL

$$.95 < (\langle OD_i \rangle / \langle OD \rangle) < 1.05$$

or

$$.95 < (\langle X_i \rangle / \langle X \rangle) < 1.05$$

where: $\langle OD_i \rangle$, $\langle X_i \rangle$ is the average test image optical density or exposure respectively for N replicate measurements where $3 < N < 5$ for the ith field or combination of fields.

$\langle OD \rangle$, $\langle X \rangle$ is the average test image optical density or exposure respectively taken over all fields or combination of fields.

DENSITY CONTROL FUNCTION

TEST METHOD

The ability of the density control selector to allow the intentional variation in optical density from the normal value will be evaluated from an analysis of test images and/or milliapere-second (mAs) measurements obtained at each position of the density control selector at a fixed kV, attenuator thickness and tube load such that the duration of exposure obtained at the "Normal" position is greater than eight to ten times the minimum controllable exposure duration.

PERFORMANCE LEVEL

The variation in test image optical density and/or mAs with respect to the normal value shall increase/decrease in the proportion specified by the manufacturer. It is anticipated that a + 4 step control should provide an incremental exposure change of + 20-25% per step.

IMAGE RECEPTOR FIELD SIZE COMPENSATION

TEST METHOD

Variation in test image optical density as a function of image receptor size (or selected portion thereof) will be determined from an analysis of test images obtained at a fixed kV and attenuator thickness and tube load such that the exposure duration is greater than or equal to three times the minimum controllable exposure duration. This test shall be applicable to all receptor sizes (or selected portions thereof) to be utilized clinically.

PERFORMANCE LEVEL

$$.90 < (OD_i/<OD>) < 1.10$$

where: OD_i is the test image optical density obtained for the ith image receptor size (or selected portion thereof).

$<OD>$ is the average value of test image optical density taken over all image receptor sizes (or selected portions thereof).

AFC SYSTEM PERFORMANCE CAPABILITY

TEST METHOD

The capability of the automatic exposure control system to provide consistent test image density over a broad range of imaging techniques and attenuator thickness will be determined from an analysis of test images obtained for attenuator thicknesses ranging from 5 to 35 centimetrs, tube potentials ranging from 50 kV to the maximum kV of the system, and tube loads such that the exposure duration for the minimum attenuator thickness at a given kv is greater than or equal to twice the minimum controllable exposure duration.

PERFORMANCE LEVEL

1. For a fixed attenuator thickness the maximum variation in test image optical density as a function of kVp shall not exceed + 0.3 CC of the average value of test image optical density taken over all kVp's at this attenuator thickness.

2. For a fixed kVp the maximum variation in test image optical density as a function of attenuator thickness shall not exceed + 0.3 OD of the average value of test imge optical density taken overall all attenuators thickness at this kVp.

Automatically control led exposures which equal the maximum allowable exposure duration shall not be included in the above analysis for determination of acceptable performance.

AEC MAXIMUM ALLOWABLE EXPOSURE DURATION

TEST METHOD

The maximum exposure duration which can be obtained under automatic exposure control will be determined from the measurement of exposure duration and/or mAs. The AEC field(s) shall be blocked with a 6 millimeter (mm) thick lead sheet, large enough to cover the field(s) refrain sense area(s) The field size shall be adjusted to a size smaller than that of the lead sheet and an automatically controlled exposure initiated at 60 to 70 kV. The operator controlled density setting shall be set to maximum density. For those systems requiring the operator to manually select a back-up time and the tube load (mA) the time shall be selected to provide an mAs greater than the allowed maximum for automatic control led exposures but less than that allowed by the single exposure radiographic tube rating chart.

PERFORMANCE LEVEL

1. The maximum allowable automatically control led exposure duration shall be less than or equal to 600 mAs or 60 kWs for kV's greater than or equal to 50 and shall be less than 2000 mAs for the kV's less than 50.

2. Any automatically controlled exposure which is terminated by the maximum al lowed limits specified above shall be visibly indicated at the operators control and subsequent automatically controlled exposure shall be inhibited until the AEC has been manually reset.