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A Large Area X-Ray Sensitive Vidicon

by

Randall P. Luhta

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Graduate Department of Medical Biophysics
University of Toronto

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A Large Area X-ray Sensitive Vidicon

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Abstract

A large area x-ray sensitive vidicon is an alternative to the x-ray image intensifier and television camera combination (XRII/TV) currently used to produce fluoroscopic (real-time) x-ray images. The proposed x-ray vidicon utilizes an amorphous selenium (a-Se) photoconductive layer to convert the absorbed x-rays into a charge image on the photoconductor surface which is then readout with a scanning electron beam. Resolution of the x-ray vidicon is higher than the XRII/TV due to the higher intrinsic resolution of a-Se in comparison to the input phosphor of an XRII and also due to the single conversion stage (photoconductor) of the x-ray vidicon in comparison to the multiple conversion stages of the XRII/TV system. This higher resolution and higher contrast for small objects could benefit diagnostic cardiac angiography as well as interventional cardiac procedures which now frequently utilize XRII/TV zoom modes to achieve higher resolution. The quality of the fluoroscopic television image is now more important than ever since most angiographic diagnoses are made from the review of television images rather than from cine film. Also, the use of interventional procedures such as balloon angioplasty, which rely on the live television image for catheter guidance as well as management decisions, continues to increase. Signal, noise, resolution and lag of an x-ray vidicon have been analysed theoretically and indicate a medically practicable device is possible. The use of a large potential (up to 5000V) to bias the a-Se photoconductor presents a problem with respect to instability of the a-Se surface potential due to secondary electron emission. The incorporation of a suppressor mesh into the vidicon has been shown to provide stable vidicon operation. A second problem preventing the practical implementation of the device was excessive dark current when a standard (xeroradiographic type) a-Se layer was used in the x-ray vidicon. Experiments involving a-Se blocking contacts have lead to the development of an a-Se layer suitable for the x-ray vidicon. With these two problems overcome, it has been possible to build a working prototype to demonstrate proof of concept and to verify theoretical predictions.
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Fluoroscopy, the facility to view motion within a body by the use of x-rays, was first demonstrated by Roentgen 100 years ago. At the present time, over 20 million medical fluoroscopy procedures are performed per year in North America\(^1\). Fluoroscopy derives its name from the use of fluorescent materials to convert x-rays into visible light. The fluorescent material, when formed into a thin sheet or screen can produce a luminous image on its surface when placed in the path of x-rays. While fluoroscopy was performed using a fluorescent screen for more than fifty years, the image produced was dim and the early radiologist would need to work in a darkened room and dark adapt his or her eyes before the procedure. The dim image also prohibited visualizing rapidly moving organs such as the heart. To overcome these problems, various devices for amplifying the image brightness were introduced around 1950. The most successful of these, which is still in use today, is the x-ray image intensifier (XRII). The XRII is a vacuum tube device which converts the x-ray image at its input to a visible light image at its output. A typical fluoroscopic arrangement using an XRII is shown in Figure 1. X-rays are produced by an x-ray tube (located under the table) and shine through the patient onto the XRII input window. The visible image at the XRII output can then be routed to either a film camera or a television camera. Television images are viewed on a nearby monitor. An x-ray absorbing contrast agent is generally introduced into either the patient's blood, digestive tract, urinary tract, spinal fluid or reproductive tract to make the anatomy of interest more readily visible.

A simplified diagram of the internal structure of an XRII system is shown in Figure 2. Within the XRII itself, the x-ray image is first converted to an optical image at the input phosphor, then to an electron image by the photocathode, then finally back to an optical image at the output phosphor. Lenses and mirrors provide the optical coupling between the XRII and cameras. The television camera in the system contains a light sensitive vidicon tube which uses a photoconductor and a scanning electron beam to convert the optical image from the XRII to an electronic video signal. Each of the many conversion and coupling stages within the XRII system is responsible for some loss in image quality. In particular, light scatter within the XRII input and output phosphors is an important source of image blur.
Figure 1. Fluoroscopy using an X-ray Image Intensifier system.

Figure 2. Principal components of an X-ray Image Intensifier system.
A significant improvement in image quality should be possible by removing the XRII from the system and making the vidicon directly sensitive to x-rays. To do this, the area of the vidicon photoconductor would need to be made much larger in order to accommodate images from the human body, and it would also need to be made much thicker in order to efficiently absorb x-rays. A diagram of the proposed large area x-ray sensitive vidicon is shown in Figure 3. Its two main components are an x-ray photoconductor and a scanning electron beam, both of which are housed in a vacuum enclosure. The x-ray photoconductor is coated onto an x-ray transparent and electrically conductive substrate which are collectively known as the target. In operation a large positive potential is applied to the substrate while the scanning electron beam deposits electrons on the free surface of the photoconductor to charge it to ground potential. The resulting electric field within the photoconductor is necessary to make it sensitive to x-rays. When an x-ray photon is absorbed, charges are created within the photoconductor which, in turn, travel to the surface under the influence of the electric field. This reduces the potential across the photoconductor and causes the surface potential to become positive at that point. The x-ray image is, therefore, represented by a pattern of electric potential on the free surface of the photoconductor. To readout the image, the electron beam sequentially deposits electrons at each point on the photoconductor surface recharging it to its original potential (ground). Once at ground potential additional electrons in the beam are repelled. The current required for recharge can be measured in the external circuit connected to the conductive substrate. This current, when amplified, forms the video signal which carries the x-ray image information to the viewing monitor. The signal is used to control the brightness of the scanning spot in the television monitor and so the image produced is directly related to the pattern of x-rays absorbed. Control signals to synchronize the vidicon and monitor are also required.

The single photoconductive conversion stage of the x-ray vidicon offers a distinct advantage over the multiple stages of an XRII system since many sources of image deterioration are eliminated. In addition, the intrinsic resolution of the photoconductor is higher than that of the XRII input phosphor. In a phosphor, light scattering occurs within the layer, but in a photoconductor, the charges created are pulled by an electric field along lines perpendicular to the surface. Blurring or loss of resolution in the photoconductor is, therefore, minimal. The dominant factor controlling resolution in the x-ray vidicon is the diameter of the electron beam incident on the photoconductor surface. This is in turn related to the number of lines chosen to form the television image.

The fluoroscopic procedures which can most benefit from improved resolution are diagnostic coronary angiography and interventional fluoroscopic procedures such as coronary balloon angioplasty. These procedures play a leading role in both the detection as well as the treatment of coronary heart disease.
Figure 3  Principal components of a large area x-ray vidicon.
Heart disease is responsible for approximately one third of all deaths in North America\(^3\). In the past, angiographic diagnosis was made from XRII images that were recorded on cine film, while the television image was used only for catheter guidance. Today, due to improvements in technology, diagnosis is routinely made from the television image. A high quality television image is also required in interventional cardiac procedures for both catheter guidance as well as strategic treatment decisions. To improve resolution within a specific area of interest, XRII zoom modes may be used. This involves changing electrical potentials within the XRII such that the image produced at the output phosphor (and television monitor) corresponds to a smaller field of view at the input. The frequent use of XRII/TV zoom modes in cardiac fluoroscopy indicates that improved resolution is desirable.

II. CORONARY ARTERY DISEASE

A. CORONARY ATHEROSCLEROSIS

Cardiovascular Disease (CVD) is the foremost cause of death in Canada as well as in other industrial societies. Recent statistics show that in 1992, 39% of all deaths in Canada were due to CVD, which includes coronary artery disease, stroke, valvular heart disease and other heart diseases\(^3\). This exceeds the total number of deaths in 1992 due to all forms of cancer. Cost of CVD to the Canadian economy is $8.3 billion per year in medical care, drugs and disability pensions and accounts for 21% of the cost of health care\(^3\).

Coronary artery disease is the result of a disease process known as atherosclerosis which involves the formation of plaques on the internal walls of arteries resulting in a significant narrowing of the lumen. Other arteries commonly affected by atherosclerosis include the carotid, femoral and iliac arteries as well as the aorta. In the case of the largest artery, the aorta, (22-38 mm diameter), it is not generally narrowing of the lumen which causes problems, but rather a separation of the internal and external layers of the aorta - a problem called a dissecting aneurysm\(^4\). In coronary arteries that are significantly narrowed, the reduction in blood flow can cause ischemia of the myocardium. A thrombus at the plaque site can also cause a total occlusion and subsequent infarction (i.e., death) of myocardial tissue. Coronary artery disease accounts for the greatest percentage (56.7%)\(^3\) of CVD and the ability to image the coronary arteries clearly is crucial to its management.
Healthy arteries are composed of three main layers, the intima, the media and the adventitia\textsuperscript{5,8,9}. The innermost layer, the intima, is composed of connective tissue and a monolayer of endothelial cells next to the lumen. The endothelial layer is non-thrombogenic and allows oxygen and other substances to pass through to the intimal and medial layers. The endothelium is also responsible for producing extracellular matrix components, growth factors and vasoactive substances. Surrounding the intima the medial layer is composed of circumferentially oriented smooth muscle cells as well as elastin and collagen. Its primary role is to produce vasodilation and vasoconstrictive action. At the inner and outer surfaces of the media are two thin sub-layers known as the internal and external elastic lamina. These two layers are perforated allowing the passage of cells. The outermost layer, called the adventitia, is composed of loosely arranged connective tissue and has primarily a structural role.

The most widely accepted explanation of atherosclerosis initiation and progression is the response to injury theory\textsuperscript{9,10,11}. According to this theory, atherosclerosis begins with an injured or functionally altered endothelial layer. The tendency for lesions to form at branches and bifurcations indicates that wall shear stress and other haemodynamic factors have a primary role\textsuperscript{9,12}. Other factors implicated in endothelial disruption are high levels of blood lipids (hypercholesterolemia), hypertension, infection and chemical irritants in cigarette smoke. The first signs of endothelial disruption are an abnormal adhesion of monocytes and an increased permeability to plasma proteins and low density lipoproteins (LDLs). Monocytes subsequently migrate into the intima where they are transformed into macrophages. The macrophages then absorb large quantities of LDLs and become foam cells. This stage of atherosclerosis is characterized by a localized yellowish appearance on the inside surface of the artery, known as the fatty streak. These streaks can be found in all persons by three years of age\textsuperscript{12}.

The fatty streak itself has no clinical significance but may lead ultimately to the atheromous plaque. Toxic substances secreted by macrophages can lead to a denudation of the endothelial layer causing platelets to adhere to the exposed intima. Platelet Derived Growth Factor (PDGF) and other mitogenic and chemotactic factors are released by the platelets and macrophages. This promotes the migration of smooth muscle cells into the intima where they proliferate and produce extracellular matrix components. A fibrous plaque is thus formed which is characterized by a glistening white appearance due to the smooth muscle cells. Most plaques also have a semi-liquid lipid core beneath the fibrous cap. It is believed that plaque formation is episodic, with each episode of damage and repair resulting in an increase in plaque size\textsuperscript{13,14}. Like the fatty streak, the normal fibrous plaque is usually not clinically relevant and can be found in most persons by their late twenties\textsuperscript{12}. During the initial growth of a plaque, the outside diameter of the artery increases to accommodate the extra volume and the decrease in lumen diameter is minimal\textsuperscript{11}. 
As the plaque progresses, its centre becomes necrotic, the fibrous cap begins to lose structural integrity, calcium deposits form in the fibrous tissues and the lipid core includes both liquid as well as crystallized cholesterol and cholesterol esters along with necrotic debris. The plaque may also crack, resulting in a thrombogenic reaction and the incorporation of blood components into the plaque. The lesion is now called a complicated plaque and has a reddened appearance due to incorporated erythrocytes. Complicated plaques generally occupy greater than 70% of the original lumen diameter (70% stenosis). Plaques can be categorized into one of three shapes, central, eccentric slit-like and eccentric polymorphous. Central plaques have a uniform narrowing around the vessel circumference and account for 31% of all advanced plaques. Eccentric slit-like plaques (29%) appear as a narrow slit extending nearly to the edge of the original lumen and eccentric polymorphous (40%) refer to all shapes that are neither central nor slit-like.

Coronary atherosclerosis is not considered clinically significant until a stenosis of >50% (percentage of lumenal diameter occluded) occurs. Symptoms of coronary atherosclerosis can either be chronic (e.g. angina) or acute (e.g. heart attack). Angina, a crushing pain centred in the chest and radiating to the neck and arms that occurs during exercise or stress testing is associated with a stenosis of 70-80% and will subside within a few minutes of stopping the exercise. Angina that occurs while at rest is associated with a stenosis of 80-90%. Severe stenosis causing chronic ischemia of the myocardial tissue can lead to congestive heart failure in which a reduced ventricular output results in a backpressure of blood and congestion in the lungs and liver. Unstable angina refers to anginal pain that is erratic and is caused by either transient thrombosis or plaque swelling. This type of angina is often called preinfarction angina since it signals a possible heart attack and should be considered a medical emergency. A heart attack occurs when a coronary artery becomes totally occluded, usually by thrombosis or coronary spasm at the site of a stenosis. A thrombosis is usually caused by the acute erosion of a plaque surface or by a plaque that splits and exposes its highly thrombogenic core to the lumen. A heart attack can have various outcomes. If the affected myocardial tissue receives blood from collateral flow or if the thrombus is lysed quickly (or the spasm is relieved) then the person can recover without serious consequences. If the myocardial tissue remains ischemic for more than a few minutes, it will begin to die or infarct (acute myocardial infarction). The myocardial tissue does not die all at once, however. Animal studies have shown that 55% of the ischemic tissue can remain viable after 40 minutes, and 33% can remain viable after 3 hours. Persons with >25% of infarcted tissue in the left ventricle can expect ventricular dysfunction, while persons with >40% infarcted tissue usually suffer intractable heart failure and cardiogenic shock. The main danger in heart attack is ventricular fibrillation caused by the ischemia and accounts for most of the deaths due to heart attack. Unfortunately, 60% of heart attacks or sudden death (death within 1 hour) occur in persons who have no prior warning symptoms sufficient to incur medical
evaluation or treatment\textsuperscript{16}.

B. THE DETECTION OF CORONARY ARTERY DISEASE

When atherosclerotic disease of the heart is suspected (chest pain, heart attack, congestion of the lungs or liver) a number of diagnostic tests can be performed. A standard chest film can reveal an enlarged heart due to congestive heart failure as well as calcification in the myocardium, valves and coronaries\textsuperscript{17,18}. Heart function can be evaluated using a cardiac stress test in which blood pressure and ECG are measured while an increasing level of exercise is performed on a treadmill or bicycle. Characteristic patterns in the ECG waveform are associated with heart disease\textsuperscript{7}. If a recent myocardial infarction is suspected the blood can be tested for an abnormally high level of certain enzymes such as creatine phosphokinase (CPK). The infarcted tissue releases this enzyme within 3 to 6 hours of the heart attack and the concentration returns to normal in about 3 days\textsuperscript{7}. Two nuclear medicine studies are commonly used to functionally image the myocardial tissue\textsuperscript{17,18,19}. A myocardial perfusion scan involves the intravenous injection of \textsuperscript{201}Tl-chloride while exercising. Thallium 201 acts as a potassium analog and its perfusion or lack of perfusion into the myocardium can be seen in a gamma camera image. A myocardial infarct scan uses \textsuperscript{99m}Tc- pyrophosphate which binds to calcium in the infarcted tissue. This test is used to complement the ECG and CPK tests.

While the above tests allow the cardiologist to confirm the presence of heart disease and possibly demarcate the disease to a particular region of the heart, they do not provide information on the exact location of the stenosis or other abnormalities. With respect to the coronary tree, the primary information sought by the cardiologist is the location and degree of any stenosis. This information is needed to choose and plan a therapeutic treatment such as coronary bypass surgery or angioplasty. High resolution images of the coronary tree are provided by x-ray angiography. This procedure involves the direction of a catheter by fluoroscopic guidance from either the brachial artery of the arm or femoral artery of the leg toward the heart and into the coronary artery of interest. Once the tip of the catheter is located at the origin of the coronary artery, an injection of x-ray opaque contrast agent is made and the images provided by the XRII are recorded. The contrast agent fills the lumen of the coronary tree providing an image of its internal geometry. An example of a coronary angiogram and stenosis is shown in Figure 4. The degree of stenosis is determined by comparing the diameter of the lumen within the stenosis to the luminal diameter just upstream or downstream. This can sometimes underestimate the degree of stenosis if diffuse disease is present.
Figure 4. Coronary angiogram with a selective injection of contrast agent into the right coronary artery. A severe stenosis is shown.

Figure 5. Coronary arteries of the heart.
The imaging device most commonly used to perform cardiac angiography is a 9” x-ray image intensifier (XRII) in which the output can be directed to a 35 mm cine film camera or to a television camera for live viewing. The XRII system is located above the patient and the x-ray source is located under the patient table. Three fields of view are selectable on the XRII which are approximately 9”, 7” and 5” in diameter. The 7” mode is used for most of the coronary imaging while the 9” mode is used for ventriculography and catheter guidance. Based on televised images in the 7” mode, the cardiologist may wish to obtain a 5” magnified view of a particular lesion. The television cameras most often used in cardiac XRII systems are the Plumbicon and Saticon type with ~1000 lines of resolution and low lag. Lag refers to a residual signal that persists after illumination has been removed and results in the appearance of a smear behind moving objects.

During catheter placement a low exposure rate of 3-5 μR/frame to the XRII is used (7” mode). When the catheter is in place, the exposure rate is increased to ~30 μR/frame, the cine film camera is engaged and the contrast injection is made. The main coronary arteries of the heart are shown in Figure 5. A standard diagnostic examination consists of four views of the left coronary arteries (left main (LMCA), left anterior descending (LAD) and circumflex (CX)), two views of the right coronary artery (RCA) and one left ventriculogram. In addition, a few extra views are typically taken to elucidate a particular lesion, often in the 5” magnified mode. The left and right coronary arteries are initially about 4.5 and 2.5 mm in diameter respectively, and eventually branch and narrow to sub-millimetre dimensions.

It is common to move the XRII (in 7” mode) a small amount to follow the region of maximum opacity as it moves from an upper to a lower region of the heart. This motion could be avoided if a larger field of view, covering the entire heart, could be obtained without sacrificing the resolution provided by the 7” field of view. In an XRII/TV system, the field of view is displayed as a circle within the rectangular monitor screen. This is because both the XRII output phosphor and the light sensitive vidicon photoconductor are circular and the vidicon overscans the photoconductor to maximize resolution. In an x-ray vidicon, the zoom field of view is rectangular and fills the full area of the monitor. The x-ray vidicon will, therefore, have a larger image area when compared to an XRII/TV image of the same height. This may provide the extra area needed to cover the entire heart and to avoid movement of the patient or x-ray vidicon.

When panning is required, for instance, in the 5” field of view, the x-ray vidicon has the advantage that it can pan the zoom mode field of view within the full field of view. In an XRII system, the zoom mode field of view is fixed to the center of the full field of view. When an XRII/TV system is aligned for a
particular view, the cardiologist knows in advance the motion sequence that will be required. With an x-ray vidicon the device could remain stationary relative to the patient and the panning motion performed electromagnetically within the device. This would eliminate any unsteadiness or vibration associated with a mechanical motion and could free the cardiologist to concentrate on the monitor images. Preprogrammed panning sequences are also possible.

In an XRII system, the XRII and x-ray tube can rotate about the long axis of the patient. This allows the cardiologist to obtain perpendicular views of the same anatomy and to avoid structures such as the spine. Perpendicular views are important in evaluating eccentric stenosis and when vessels in one image overlap. In many cases, cranial and caudally angulated views, that is tilting the XRII/TV in the cranial or caudal direction up to 45° are also required to prevent some vessels from being viewed as either end-on or overlapping. This is especially true when imaging the left main coronary artery and the proximal regions of the left anterior descending and circumflex arteries. Advanced stenosis in this region is considered serious and a clear view of these vessels is important. In an XRII/TV system a large border exists around the field of view in zoom mode since the device can only zoom to its centre. This border in combination with an angulated view means that the XRII cannot get as close to the heart as one would like without the edge of the XRII colliding with the patient. Getting the XRII close to the heart improves resolution by reducing focal spot unsharpness. Focal spot unsharpness is a problem in angulated views since it is usually necessary to switch from a small (0.6 mm) to a large (1.2 mm) focal spot in order to increase x-ray tube output to penetrate the greater length of tissue. Interference between the XRII and the patient is one reason why XRIIs larger than 9" are not used for cardiac angiography. An x-ray vidicon could help to remedy the problem of angulated views since the zoom field of view can be located at the edge of the device nearest to the patient. This would allow the x-ray vidicon to be located closer to the heart and, therefore, improve resolution.

A problem encountered in x-ray imaging is that when trying to image increasingly smaller structures, the number of x-rays used to form the image of the structure decreases. At some point, the number of x-rays used to form an image of the structure is too small to make it distinguishable from statistical fluctuations in the number of x-rays that make up the background. In the case of small coronary vessels, as smaller vessels are considered, both the vessel width in the image plane and the vessel thickness in the x-ray direction decrease. Therefore, despite any improvements in resolution offered by an x-ray vidicon, it is the reduced number of x-rays used to form the vessel image that becomes the dominant factor in determining the minimum vessel size that can be seen. Coronary structures for which improved resolution is likely to provide a significant improvement in visibility are those which are narrow in the image plane,
but are long in the perpendicular or x-ray direction. An example of such a structure is the eccentric slit-like stenosis\textsuperscript{14}. When this type of stenosis is encountered, the cardiologist will purposely choose a view such that the projection of the stenosis is narrowest. This is done as part of the procedure for determining the degree of stenosis. In this case, although the stenosis is narrow in the image plane, it has a considerable thickness in the x-ray direction and, therefore, has a sizable image signal for which an improved resolution can be utilized to sharpen the vessel image. Thus, increased resolution should allow a more accurate assessment of luminal narrowing when the slit-like stenosis is encountered.

The use of digital capture, processing, storage and display has become widespread in cardiac angiography. The ability to freeze-frame or review images reduces patient x-ray exposure and aids in interim evaluation. Traditionally the cine film when developed served as the basis for diagnosis and archiving. Today the improved quality of digital television images allows them to be used for diagnosis but the recording and archiving of cine film continues. An eventual conversion to digital archiving at all institutions is expected. The fact that an x-ray vidicon lacks the cine film capability should, therefore, not present any problems.

While cardiac angiography provides invaluable information to select and plan subsequent therapy, it does unfortunately have risks associated with it. Complications due to catheterization of the heart and contrast injection occur in a few percent of procedures\textsuperscript{4,18}. These include myocardial infarction, vasovagal reactions (hypotension, pain), arrhythmias, perforation and local problems at the brachial and femoral arteries (thrombus, haemorrhage, infection, haematoma, embolism). To reduce the risk associated with the iodine containing contrast agent and its ionic nature, a more expensive, but less ionic contrast may be selected in some cases\textsuperscript{4,17}. The radiation exposure to the patient's surface for a complete exam\textsuperscript{4} is typically 50 R. The risk of future cancer induction from this exposure, however, is small compared to the risk of catheterization. The risk of mortality\textsuperscript{4} for cardiac catheterization is about 0.14\% and occurs mostly in patients over the age of 60 and in those with disease of the left main coronary artery (LMCA).

C. TREATMENT

The treatment of atherosclerotic disease begins with changes in diet, lifestyle and risk factors. A reduction in fat intake (especially LDLs), achieving a lean body mass, regular exercise and not smoking will significantly slow the progression of atherosclerosis and reduce the risk of heart attack\textsuperscript{16,12,11}. If a cardiac angiogram has been performed, then one of three treatments will most likely be selected, drug therapy, bypass surgery or percutaneous transluminal coronary angioplasty (PTCA). The drugs most often prescribed are nitroglycerin which reduces angina by dilating coronary arteries, and propanolol which
controls abnormal heart rhythms and reduces high blood pressure. For 60% of patients who have had a cardiac angiogram, however, revascularization is recommended. Surgical bypass involves the use of saphenous (leg) vein grafts or a redirection of the left internal mammary artery to bypass stenotic regions of the coronary tree. Despite the extreme invasiveness of this operation which involves stopping the heart, the death rate is less than 1%. Immediate relief from angina is achieved in most cases and life expectancy is definitely improved in critically ill patients such as those with left main coronary artery disease. An improvement in life expectancy is also believed to occur for the majority of patients (non-critically ill), but has not been proven at this time.

A less invasive treatment used in about half of patients requiring revascularization is angioplasty which involves the use of a specialized catheter under fluoroscopic guidance. An atherectomy catheter can be used to mechanically remove tissue at the stenotic site. Some designs cut and capture the lesion tissue while others, using high speed rotation, abrade the tissue into microscopic particles that are carried away by the blood. Laser angioplasty uses a fibre-optic catheter and a high power laser to ablate the lesion tissue. The most successful and widely used angioplasty treatment, however, is balloon angioplasty, in which a balloon is inflated at the stenotic site to widen the lumen.

A balloon (i.e., dilation) catheter can be introduced at either the brachial or femoral sites through a previously inserted guiding catheter. A guide wire (0.3-0.5 mm diameter) that extends beyond the hollow dilation catheter is first navigated past the stenosis using fluoroscopy. The dilation catheter is then advanced into position along the guide wire and is inflated with a solution of saline and contrast agent to a pressure of about 150 psi. The pressure is held for about 40 to 60 seconds during which the downstream circulation is cut off and the patient feels anginal pain. This inflation time is short enough, however, to prevent infarction. After inflation, the improvement in lumen diameter is checked using a contrast injection. Inflation is typically repeated 2 or 3 times until the desired result is achieved. The dilation catheter is about 1 mm in diameter and inflates to a predetermined diameter in the range of 2-4 mm. Most of the improvement in vessel diameter is a result of plaque fracturing and vessel overstretching. The compression of plaque material itself is minimal. The success rate of balloon angioplasty is about 90% with unsuccessful attempts usually due to a failure to cross the stenosis or a failure to achieve adequate lumen diameter after several inflations of the balloon.

Balloon angioplasty carries a greater risk than diagnostic angiography. The greatest risk is total occlusion of the dilation site due to thrombus, spasm or flap separation, which may require emergency bypass surgery. Embolism of plaque material and vessel rupture are rare. Mortality in patients with single
vessel disease is about 0.2% and for patients with multi vessel disease it is about 1%. Restenosis occurs in about 25% of patients within 9 months following treatment. Additional angioplasty or other treatment is then performed.

Management decisions are required more frequently in the course of coronary angioplasty than in routine diagnostic coronary angiography. Since the cardiologist has to rely on the review of television images for such decisions, these images must be of the highest quality. Ischinger argues that "the quality of the fluoroscopic TV image perhaps more than any of its other features influences the selection of a system for a laboratory dedicated primarily to interventional cardiology". The use of 1000 or more lines of resolution is considered essential as is the capability for freeze-frame and slow motion playback. In addition to gauging the improvement in lumen diameter the cardiologist also looks for structure within the stenosis such as tears or flaps. Flaps and tears can result from catheter and guidewire damage to the intima or from a separation of the fibrous cap of a plaque from the vessel wall following angioplasty. If unattended, the flap or tear can potentially lead to a total vessel blockage and acute myocardial infarction. The intimal flap or tear is another example of a structure which can produce a narrow projection in the image plane, but have a considerable thickness in the x-ray direction. Improved resolution could aid in detecting this important condition.

An increasingly important adjunct to balloon angioplasty is the placement of stents in the coronary lumen. At the present time, about a half of all patients receive one or more stents during angioplasty. A stent is a hollow metallic tubular structure that is placed at the stenotic site following balloon dilation. The stent can be self expanding or expanded by the use of a balloon. Stents are used to prevent restenosis or to repair flaps that have caused, or may cause, blockage. The placement of stents is critical. Failure of the stent to cross the entire lesion can result in restenosis at the stent opening. The increasing use of stents, therefore, further increases the demand for improved television images in cardiac imaging.

D. ALTERNATIVE IMAGING MODALITIES

In addition to the chest x-ray and nuclear medicine studies mentioned earlier, other non-invasive methods of evaluating the heart include CT, MRI and ultrasound. Conventional and spiral CT can be used to image the aorta for dissection or aneurysm while ultrafast CT with a slice acquisition time of 50 - 100 ms can image the heart at different phases of the cardiac cycle. This allows evaluation of functional parameters such as wall motion, stroke volume, ejection fraction and regurgitation. The evaluation of coronary arteries, however, is severely limited by resolution. MRI images show signal voids or signal
enhancement in regions of blood flow depending on the type of pulse sequence chosen\textsuperscript{40,17}. Using ECG gating, an image of the heart at one or more specific phases in the cardiac cycle can be obtained to evaluate cardiac dimensions and function. Gradient echo techniques allow for cine MRI in which 16 - 30 images can be obtained within the cardiac cycle\textsuperscript{18}. These images played in a movie loop, can be used to evaluate wall and valve motion as well as blood flow. Recent advances in MRI now allow quantitative flow images using time of flight and phase shift techniques\textsuperscript{40}. Unlike CT angiography, MR imaging does not require the use of a contrast agent. Similar to CT, however, MRI allows only the most proximal regions of the coronary vessels to be seen.

Echocardiography is a safe and cost effective method of evaluating cardiac function and pathology. Two dimensional (B-mode) and M-mode ultrasound allows measurements of cardiac morphology and wall motion to be made. Abnormal wall motion is a strong indicator of ischemia in the myocardium, and an estimate of the location and extent of the ischemia can usually be made\textsuperscript{41,42,18}. Echocardiography is often used to complement other cardiac evaluations such as ECG and nuclear medicine studies\textsuperscript{17}. Ultrasound is also particularly good at detecting pericardial effusion (fluid accumulation within the pericardial sac surrounding the heart) and aortic aneurysm and dissection. Doppler ultrasound allows quantitative measurement of blood velocity and flow to be made, which is useful for detecting valvular disease and cardiac shunts. Recently, minimally invasive transesophageal ultrasound has provided cardiac images with a significant improvement in resolution over externally obtained images. The LMCA (see Figure 5) and proximal regions of the left and right coronaries can be distinguished with this method\textsuperscript{18}. The detection of coronary stenoses, however, remains limited. New techniques involving ultrasonic contrast agents may improve echocardiography.

In an effort to visualize the coronary arteries better, new invasive catheter based imaging methods are being developed. These include angioscopy, intravascular ultrasound, and intravascular MR. Angioscopy is a method of optically imaging the inside of a vessel by means of a fibre-optic imaging catheter. A saline solution is used to displace blood and provide a clear window to assess the lumen diameter and wall condition. Angioscopy has proven to be valuable in evaluating vessel changes following balloon angioplasty\textsuperscript{43}. In the case of abrupt closure, the most common complication of angioplasty, angioscopy can be used to easily distinguish between flap closure and thrombus and, therefore, aid in selecting the appropriate treatment\textsuperscript{44}. Problems with angioscopy include an inability to properly displace blood in some cases, and an inability to properly navigate the catheter in narrow locations. The added cost and extended procedure time are also important factors to consider when deciding to do angioscopy. Intravascular ultrasound (IVUS) uses one or more high frequency ultrasound transducers (20 - 30 MHz) located at the
end of a catheter to produce cross-sectional images of a vessel. The two most common configurations are a single transducer, in which the beam is mechanically rotated, and a segmented ring of transducers forming a phased array\textsuperscript{45}. Images from IVUS allow individual layers of an artery to be distinguished and are comparable to histological sections\textsuperscript{46}. The ability to determine plaque composition is important in selecting an interventional procedure such as balloon angioplasty, atherectomy or laser angioplasty\textsuperscript{47,45}. IVUS can also detect smaller plaques that are not detectable using x-ray angiography\textsuperscript{42}. Limitations of IVUS include an inability to traverse narrow vessels and severe stenoses\textsuperscript{48,49} and poor image quality (due to limited lateral resolution) when the transducer is not located centrally in the lumen or when eccentric stenoses are involved\textsuperscript{50,51}. New smaller and higher frequency transducers are being investigated to overcome these problems\textsuperscript{52,42}. Research is also being done to determine the feasibility of using IVUS to guide interventional procedures such as atherectomy\textsuperscript{53}. A third intravascular imaging technique involves the placement of a small magnetic resonance receive coil at the end of a catheter\textsuperscript{54,55}. Similar to an MR surface coil, the close proximity of the coil to the vessel wall greatly improves signal to noise ratio and resolution. Cross-sectional images showing vessel structure, as well as plaque structure and composition, are possible. These images could be used to select an interventional treatment or as a research tool to study the progression of atherosclerosis. Problems that prevent the routine use of intravascular MR at this time are miniaturization of the device to improve placement and severe image disruption due to patient motion. These are difficult technical problems for which solutions have yet to be found.

Coronary x-ray angiography remains the most suitable method for the detection of coronary occlusion and the guidance of interventional therapies. Non-invasive cardiac imaging techniques, while not yet able to replace x-ray angiography, provide valuable information and allow the selection of only those patients for which the risk of catheterization is warranted. Angioscopy and IVUS are a valuable adjunct to coronary x-ray angiography providing information that is not otherwise available. It does not appear that angioscopy or IVUS will soon replace x-ray angiography, but rather the three will provide complimentary information.

III. THE X-RAY IMAGE INTENSIFIER SYSTEM

The XRII was first patented and built by Langmuir in 1937\textsuperscript{56,1}. Its gain, however, was too low for clinical use. This problem was solved by Coltman of Westinghouse in 1948 who increased the XRII brightness by miniification of the output. Today, all medical XRII’s\textsuperscript{57,58,59,60,61} are based on Coltman’s design which is illustrated in Figure 2. The x-ray input window is typically made of glass or aluminum about 1mm
thick\textsuperscript{57} while the phosphor substrate is typically made of aluminum about 0.4 mm thick\textsuperscript{57}. X-rays which pass through the input window and phosphor substrate are absorbed in the input phosphor which is CsI up to 400 \( \mu \text{m} \) thick. To reduce light scatter and improve resolution, the CsI used in the XRII is processed to produce vertical cracks which help to guide light to the surface. Light photons produced by the absorption of x-rays in the input phosphor are absorbed by the photocathode which in turn releases photoelectrons into the vacuum. A series of electrostatic lenses focus these photoelectrons onto the output phosphor while accelerating them to about 25 keV. The minifying electro-static electron optics requires that the input phosphor/photocathode be curved\textsuperscript{52}. This curvature introduces a spatial distortion into the image known as pincushion distortion. It is characterized by an outward stretch at the edges of an image which cause a square to be distorted into a pincushion shape. The output phosphor is typically ZnCdS:Ag about 1" in diameter and 4-8 \( \mu \text{m} \) thick. The output of the XRII is about ten thousand\textsuperscript{61} times brighter than a phosphor screen alone. This brightness gain is due to the combined acceleration and minification of the photo-electron image. Of the many image conversion stages, the greatest loss of resolution occurs in the input phosphor followed by the output phosphor and then the electron-optics. The output window is specially designed to prevent glare due to internal reflections. The lenses used outside the XRII to couple the visible image on the output phosphor to the television camera or 35 mm cine film camera are relatively large to maximize the light coupling efficiency. These large high quality lenses are an expensive part of the XRII system.

The manufacture of an XRII involves the specialized handling of materials and close mechanical tolerances. During manufacture, the CsI phosphor must be handled in a dry atmosphere to avoid deterioration, and the photocathode must be formed and maintained in a high vacuum at all times. Tolerances on internal electrodes is stringent, for example, the photocathode surface must be positioned within 0.15 mm over its 220 mm width\textsuperscript{58}. These measures contribute significantly to the cost of manufacturing an XRII. Despite its many parts and construction difficulties, the XRII has improved considerably since its introduction and represents a mature technology.

Many of the problems associated with an XRII can be overcome by using an x-ray vidicon. Pincushion distortion caused by a curved input receptor is eliminated by the use of a flat photoconductor. The tolerances on most of the x-ray vidicon electrodes are relaxed in comparison to an XRII and most x-ray photoconductors can be safely handled in air. This greatly simplifies construction and reduces cost. The x-ray vidicon does not form an intermediate light image and, therefore, eliminates all sources of optical glare and the need for expensive lenses. These, along with previously mentioned advantages, (higher resolution of a photoconductor and more flexible pan and zoom modes), make an x-ray vidicon an
Another x-ray imaging device currently being developed as an alternative to the XRRI/TV and x-ray vidicon systems is the flat panel imager. These devices consist of a glass substrate onto which a two-dimensional matrix of x-ray detectors is fabricated. During operation, the absorbed x-rays are converted to an electrical charge using either a coupled phosphor and photodiode\textsuperscript{63,64,65} or a semiconductor such as amorphous selenium\textsuperscript{66,67}. This charge is stored on capacitors at each pixel in the matrix. Readout of the charge can be done with either a thin film transistor matrix or a diode matrix. Amorphous silicon and cadmium selenide are the two semiconductors currently being used for fabrication of the readout structure. Advantages of the flat panel imager are its fast readout, extreme compactness and freedom from spatial distortion. The main problems to be overcome before widespread application are improving the manufacturing yield and reducing electronic readout noise. The problem of noise is greater for fluoroscopic readout which uses a much lower x-ray exposure per frame than radiographic readout. A limitation of flat panel imagers when compared to the XRRI/TV and x-ray vidicon systems is an inability to zoom, that is improve resolution by applying the readout matrix to a smaller field of view. The zoom feature of the XRRI/TV is heavily utilized in modern cardiac angiography. To achieve both the high resolution of an XRRI/TV zoom mode and the full field of view of non-zoom mode, a flat panel would require a very large matrix (\(\geq 2000 \times 2000\)) of relatively small pixels (\(-100 \mu m\)). Development of such a panel capable of real time readout and operating at the low exposure rates used in fluoroscopy represents a great technical challenge from the point of view of yield and noise and will probably not be achieved for some time. Most people in the field of x-ray imaging believe that the flat panel will eventually be the preferred x-ray detector for cardiac angiography. A time window of opportunity, therefore, probably exists for the x-ray vidicon due to its zoom mode capability and its lower initial cost.

\textbf{IV. THE X-RAY VIDICON}

\textbf{A. HISTORY}

The potential advantages of an x-ray vidicon were recognized in the 1950's and a few unsuccessful attempts to build a medically useful device were made. The history of these devices can help to identify possible problem areas and avoid the repetition of unproductive avenues. In any design, it is important to ensure that the problems encountered in previous designs have been solved.
In the literature there appears to have been only 5 attempts to build an x-ray vidicon of 4" in diameter or larger. Many 1" diameter x-ray vidicons have been reported both experimentally and commercially. The first report of x-ray images produced by a vidicon was in 1954 by Cope and Rose. They used a 1" diameter vidicon with a 25 µm thick amorphous Selenium (a-Se) photoconductor. They were able to produce live x-ray images of small objects as well as show the existence of x-ray quantum noise. In that same year, Heijne, Schagen and Bruining were also able to show x-ray images on a 1" vidicon with a 5 µm thick PbO layer. These vidicons were very similar to the light sensitive Sb₂S₃ vidicon announced in 1950 by Weimer et al.

The first large area x-ray television camera was reported by Keller and Ploke in 1955. It used an a-Se photoconductor 150 µm thick and could produce images 30 cm x 30 cm in size. The potential used across the a-Se layer was about 1000V. Due to difficulties in achieving stable readout with a low velocity beam such as used in a vidicon, they decided to use a high velocity beam of 1 keV. Their camera can therefore be considered to be a high velocity vidicon or else a photoconductive iconoscope (high velocity readout camera that was a precursor to the vidicon). The reported x-ray sensitivity and very low photoconductive lag for a layer 150 µm thick indicates that the a-Se was of high quality. A severe problem with the camera was the presence of electron bombardment induced conductivity (EBIC) in the a-Se. This occurs when beam electrons impinging on the a-Se are energetic enough to create electron-hole pairs which appear as a high dark current. For this reason the camera was not able to produce continuous live images although under special circumstances good quality images could be produced for about 30 seconds. It is now known that the problem of EBIC can be solved by a surface coating of Sb₂S₃ or some other suitable material. A problem common to high velocity readout is shading caused by the redistribution of secondary electrons which is the reason it is rarely used. This problem was not mentioned in their paper but must have been present. If only a stable low velocity readout could have been achieved in their tube they would quite likely have had a medically useful device.

The second large area vidicon reported was by Jacobs and Berger in 1956. The tube was 12" in diameter with a 150 µm PbO layer. A lower potential across the layer (200V) and the lower secondary emission of PbO allowed the tube to be operated with a low velocity readout and was therefore a true vidicon. An 8" O.D. tube was also produced. Sensitivity of the tube was quite high with a noise level corresponding to about 33 µR/s. This is adequate for medical use, and in 1959 the system was tested in six medical clinics. Results from one hospital indicate that the system "produced excellent detail" and exposure rates were comparable to those needed for an XRII. Unfortunately, the tube deteriorated rather rapidly as a result of x-ray exposure. The deterioration included persistent after-images which persisted
longer with use, white spots, mottled non-uniformity, and loss of sensitivity. This deterioration did not occur if the PbO was irradiated without an applied field across the layer. The problem was discovered to be due to loss of oxygen\textsuperscript{81,88} from the PbO. Improvements have been made in PbO for use in 1" light sensitive camera tubes called Plumbicons\textsuperscript{82,83}, but to date no reports have been found involving a solution to the x-ray deterioration problem seen in thicker layers.

Another attempt to produce an a-Se large area vidicon was made in 1960 by Smith\textsuperscript{84}. The tube had an imaging area of 4" x 4". The problem of achieving stable low velocity scanning encountered by Keller and Ploke was addressed by using a curved target surface that was concave when viewed from the side scanned by the electron beam. With the appropriate radius of curvature the electron beam could be made to land perpendicular to the target surface at all points as required for stability. The sensitivity of the tube, unfortunately was very low. A range of a-Se thicknesses up to 60 μm were tried and the greatest sensitivity was found for a 10 μm layer. A large amount of photoconductive lag was also reported. This indicates that the quality of the a-Se used was low. Also the maximum potential used across the a-Se layers was about 120V which is insufficient for layers greater than about 20 μm. A second attempt to produce a PbO large area vidicon was made in 1976 by Suzuki et al\textsuperscript{85}. The tube was 5" in diameter with a 15 μm PbO layer. The tube had low sensitivity and was therefore, only useful for non-destructive testing applications. The fifth and last large area x-ray vidicon found in the literature is a tube by Haque and Jacobs in 1977\textsuperscript{86,87}. The tube used a thin (9 μm) Pb x-ray to electron conversion layer and low density CsI multiplication layer similar to that used in SEC (secondary electron conduction) cameras. Sensitivity of the tube was low for x-ray energies in the diagnostic range and they recommend that it is best suited to x-rays energies of 80 KeV or higher. A number of experimental 1" x-ray vidicons have been reported using a-Se\textsuperscript{88,89}, CdTe\textsuperscript{90,91}, and Si\textsuperscript{92} as well as commercial\textsuperscript{93,94,95,96} 1" x-ray vidicons using a-Se, PbO, and CdSe. In all cases the photoconductor is 20 μm or less and medical sensitivity even over a small area is not achieved.

Overall, the failure of the x-ray vidicon has been due to either poor performance photoconductors or else an inability to achieve stable low velocity readout with high photoconductor potentials. If a large area x-ray vidicon is to be successful, solutions to these problems must be found.

B. PROPOSED DESIGN

Of the two x-ray photoconductors previously used in an x-ray vidicon, PbO and a-Se, only a-Se has seen extensive development for x-ray use such as in the commercial product Xeroradiography\textsuperscript{97}. The discovery
of adding As to a-Se to prevent crystallization is especially important in providing a long lasting x-ray photoconductor. Xeroradiography uses a thick (>150 \mu m) a-Se plate whose surface is initially charged to a uniform high potential. After an x-ray exposure is made, the resultant surface charge image is made visible using a toner readout method similar to a photocopy machine. Xeroradiography is known for its high quality high resolution images. These xeroradiographic type plates are, therefore, an excellent candidate for the target of an x-ray vidicon. The extremely low dark current per unit area characteristic of xeroradiographic plates is important when the total dark current over a large area must be kept low. Amorphous selenium is also easy to fabricate in large sheets and is not known to deteriorate with x-ray exposure. The proposed design is, therefore, a large area vidicon as depicted in Figure 2 along with a xeroradiographic type plate as the target.

For optimum x-ray sensitivity the potential used across the a-Se layer is many thousands of volts. This far exceeds the typical 50 volts used in a light sensitive vidicon and is known to lead to instability with respect to maintaining the desired potential on the target surface. Methods of preventing this instability are used in other non-vidicon television cameras and could be applied to the x-ray vidicon. A second problem is that the polarity of the potential across the a-Se layer in a vidicon (free surface negative) is opposite to the polarity used in Xeroradiography (free surface positive). This can result in a high dark current unless the xeroradiographic layer can be appropriately modified. Fortunately, methods used to prevent high dark current in light sensitive a-Se vidicons exist, and could be applied to the xeroradiographic type x-ray target.

C. MEDICAL REQUIREMENTS

For medical purposes an x-ray vidicon needs to meet certain technical requirements to ensure the the best use is being made of the potentially harmful x-rays that pass though the patient. One requirement is that x-ray quantum noise (grainy appearance caused by forming an image from a finite number of small spots each representing a single x-ray photon) be larger than electronic noise (unwanted signals introduced by amplifiers and other electronic components). This condition is referred to as quantum noise limited operation. It is also required that the resolution of the system be sufficiently high so that detail present in the x-ray image, as it enters the device, will be faithfully reproduced at the monitor. Finally, the lag (a persistence in the displayed image) of the device should be small enough that the image displays motion without the appearance of smear.
D. HYPOTHESIS

Research on the large area x-ray vidicon is based on the hypothesis that:

A large area vidicon utilizing a thick a-Se photoconductive layer should be capable of providing fluoroscopic images superior to the XRII/TV system at the same entrance exposure rate. This device will be of the most benefit to relatively small field of view, high resolution applications such as diagnostic and interventional cardiac angiography. To achieve the required sensitivity the a-Se layer will require a potential across it which is much larger than that used in conventional vidicons and, therefore, will require extra measures to ensure low dark current and stability of the a-Se surface potential.

V. THESIS OUTLINE

The first section of this thesis, Chapters 2 and 3, deal with the theoretical feasibility of producing a large area x-ray vidicon capable of meeting medical requirements and possibly replacing the XRII. Throughout the assessment it is assumed that the x-ray vidicon will have an imaging area of 9" in diameter, with a 500 μm thick a-Se layer, and an applied field of $10^7$ V/m. The performance of such a vidicon is compared to a modern 9" XRII/TV system for both standard fluoroscopy (used for catheter guidance) as well as cardiac cine conditions. The second section, Chapters 4 and 5, involve the solution of the two major practical problems encountered when attempting to utilize modern a-Se x-ray photoconductive layers in a large area vidicon. The first problem is maintaining electrical stability of the a-Se surface when very large potentials are used across the layer. The second problem is that a-Se layers are normally used with a positive surface charge and exhibit a high dark current when charged negatively by an electron beam. Methods for solving these two problems will be discussed. The third section, Chapter 6, describes the construction and results obtained from a 6" prototype demountable x-ray vidicon. Finally, the fourth section, Chapter 7, consists of future work and conclusions. Overall, the thesis seeks to show that a large area x-ray vidicon is a viable alternative to the XRII and has advantages that could improve diagnostic and interventional cardiac angiography.
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CHAPTER 2

FEASIBILITY OF A LARGE AREA X-RAY SENSITIVE VIDICON FOR MEDICAL FLUOROSCOPY: SIGNAL AND NOISE FACTORS*

I. INTRODUCTION

In medical fluoroscopy, the relatively low exposure rates used, present a challenge with respect to producing a directly x-ray sensitive television camera. The photoconductor layer must absorb the relatively small number of x-rays incident in a single frame (usually 1/30 s) and convert them into an electrical signal of sufficient magnitude to overcome system noise. The magnitude of signal is largely dependent on the choice and quality of the photoconductor and on the voltage impressed upon it. Noise on the other hand depends mostly on the choice of preamplifier and the stray capacitance present on the preamplifier input.

A theoretical analysis has shown that a 500 µm a-Se layer with a potential of 5000 V will provide a signal that is comparable to the signal produced by an X-ray Image Intensifier Television System (XRII/TV) for the same entrance exposure rate. The system noise of the x-ray vidicon will be larger than the XRII/TV but will be below quantum noise at the entrance exposure rates and resolutions that are relevant. The advantage of the large area x-ray vidicon over the XRII/TV is a superior Modulation Transfer Function (MTF). Signal and quantum noise at high spatial frequencies are therefore transferred with less attenuation and the signal to system noise ratio is higher.

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II. FEASIBILITY

A. SIGNAL

For a given x-ray exposure rate at the input of an x-ray vidicon the signal produced will depend on the degree of x-ray absorption in the input window; the degree of x-ray absorption by the photoconductor; and by the x-ray to electron conversion efficiency of the photoconductor.

1) X-Ray Photoconductors

Although x-ray absorption and conversion are of prime importance in choosing a photoconductor one must also consider other factors such as dark current, lifetime, lag, and ease of manufacturing. X-ray absorption is related to the atomic number \( Z \) of the photoconductor and its thickness. Thus an x-ray photoconductor should have a relatively high \( Z \). Conversion efficiency of a photoconductor depends not only on how many carriers are created by each x-ray but on whether these carriers can traverse the photoconductor thickness. For this reason a good x-ray photoconductor requires that both electrons (e) and holes (h) be mobile and that their ranges exceed the layer thickness required for efficient x-ray absorption. Dark current has two components: bulk and surface. To minimize surface injection of dark current the photoconductor must be capable of forming blocking contacts (electrical barrier to charge flow at surface). Bulk generated dark currents are a result of thermal generation. For low bulk dark current at room temperature the photoconductor must have relatively large bandgap \( E_g \), preferably \( >1.5 \) eV. In combination bulk and surface dark current should be as low as possible. The desired x-ray photoconductor must be capable of being made in a large area free of defects and at an acceptable yield. The photoconductor must not be damaged by exposure to x-rays and trapping in the photoconductor must be minimized in order to prevent photoconductive lag. The dielectric constant of the photoconductor should be low in order to reduce the capacitance of the layer and minimize a second type of lag known as beam discharge lag.

The photoconductor that best meets the needs of the large area vidicon at this time is amorphous selenium (\( a\)-Se), which has \( Z=32 \). While its x-ray absorption and conversion efficiency are not as high as other x-ray photoconductors such as PbO (\( Pb:Z=82 \), \( O:Z=8 \)) or CdZnTe (\( Cd:Z=48 \), \( Zn:Z=30 \), \( Te:Z=52 \)), it is superior in the other criteria mentioned. For instance, PbO is known to deteriorate with x-ray exposure, while CdZnTe is difficult to manufacture in large sheets. The most difficult criterion that a large area vidicon photoconductor vidicon must meet is low capacitance of the photoconductive layer (for low beam
discharge lag). The low dielectric constant (ε_r=6.3) and large thickness (500 μm) of an a-Se layer produces an acceptable capacitance (4.3 nF for 9" dia.) with respect to beam discharge lag. Other x-ray photoconductors tend to have a larger ε_r than a-Se which means they would need to be >500 μm thick. The possibility of using a photoconductor other than a-Se is discussed further in Chapter 7.

a) **Amorphous Selenium**

Amorphous selenium (a-Se) is the oldest known photoconductor. Currently it is used in the light sensitive vidicon known as the Saticon^12. Among vidicons the Saticon is noted for its low lag (photoconductive and beam discharge) and low dark current. A typical Saticon has lag which is <5% in 50 ms (3rd field in RS-170 video) and a dark current of <0.5 nA/cm². A-Se is also used as the x-ray photoconductor in a large area imaging system known as Xeroradiography^3. In Xeroradiography, an a-Se layer between 150 and 300 μm thick is vacuum deposited onto an aluminum substrate typically 9.5x14". These layers are charged with gaseous ions and readout using toner in much the same manner as a photocopier. A xeroradiographic plate, when charged with a positive surface charge, exhibits extremely low dark current^4, typically <0.01nA/cm². The reason for the much lower dark current in a xeroradiographic layer in comparison to a Saticon layer is not entirely known, but is related to the surface blocking layer and the process by which it is made (see Chapter 5). The use of a-Se in Xeroradiography makes it the only x-ray photoconductor ever used in conventional medical x-ray imaging systems. These xeroradiographic plates are well suited for use in a large area x-ray vidicon. Since the properties of xeroradiographic plates are well known, predictions of vidicon performance are easily and accurately made based on the a-Se thicknesses and bias potentials used in Xeroradiography.

2) **Window Absorption**

Since the x-ray vidicon requires that the a-Se target be held in vacuum, the x-rays must enter the vidicon through a suitable vacuum window. This window must be strong enough to withstand atmospheric pressure over a large area while at the same time be as transparent as possible to x-rays. The problem is to choose a suitable material, material thickness, and configuration which will minimize window absorption while maintaining structural integrity. This problem is the same as that encountered by XRII manufacturers and their knowledge and experience can be applied almost directly. XRIIs typically have windows made of glass, titanium, aluminum, and in special applications, beryllium. The best compromise window material for use at fluoroscopic x-ray energies in terms of x-ray transparency, scattering, strength, cost and ease of manufacture seems to be aluminum and is now the preferred choice for most medical
applications. For maximum strength, vacuum windows are made curved and both concave and convex designs are used in practice.

Glass is often the cheapest and easiest material to use as an x-ray window since the rest of the XRII or x-ray vidicon is usually also made of glass. This is the case for our prototype x-ray vidicon which has a Pyrex window ~2.5 mm thick. The composition of Pyrex glass (Corning 7740) is SiO$_2$ 80%, B$_2$O$_3$ 14%, Na$_2$O 4% and Al$_2$O$_3$ 2%.

Be has superior x-ray transmission compared to Al and glass, but is much more difficult to manufacture and hence more expensive. Be sheet must be pressure formed to produce a concave or convex shape. Be could be used for special applications such as low kVp examination of the breast.

The x-ray transmission of various window materials used in the XRII are shown in Figure 1. For our large area x-ray vidicon calculations, we will assume a 0.8 mm Al window and 0.4 mm Al substrate to match that typically used in the CsI XRII. Absorption of this window and substrate is ~11% at 90 kVp.

3) **X-Ray Absorption of a-Se**

Although the Z of a-Se is lower than would be optimal to ensure high x-ray absorption, it can be made in layers up to 500 μm thick without undue losses due to trapping. A plot of x-ray absorption versus kVp for a 500 μm a-Se (Se:Z=34) layer is shown in Figure 2. For this layer, absorption drops from 63% at 50 kVp to 46% at 120 kVp when window and substrate absorption is included. Figure 2 also shows the absorption characteristics for a 300 μm and and 400 μm CsI (Cs:Z=55, I:Z=53) layer typical of a modern XRII under the same conditions. Although the absorption properties of a 500 μm a-Se vidicon are slightly inferior to that of a 400 μm CsI XRII, the a-Se layer does have ~50% absorption over the diagnostic range and this should be acceptable for medical applications.

4) **Signal from Amorphous Selenium Versus Exposure**

For a given quantity of x-rays absorbed in an a-Se layer, the signal or number of electrons released will depend on the a-Se quality and on the applied electric field. For our purposes we will assume xeroradiographic grade a-Se (Xerox 125) and an electric field of 1x10$^7$ V/m. This field is the practical limit due to dark current and spot defects which show up at higher fields. The signal produced by an a-Se
Figure 1. X-ray transmission of various window materials used in the XRII (from de Groot\textsuperscript{5}). The same window materials are directly applicable to the X-ray Vidicon.

Figure 2. X-ray absorption of a-Se vs. kVp including the effect of input window absorption. The calculation of quantum efficiency at each kVp is based on a summation, at 1 keV intervals, of the appropriate tungsten anode x-ray spectrum and monoenergetic attenuation coefficients.
layer has been found to depend only on the total quantity of energy deposited independent of the actual x-ray photon energies in the diagnostic range\textsuperscript{7}. Thus the sensitivity of $a$-Se at a given electric field can be given by a single number. $W$ or the energy absorbed to release one electron-hole (e-h) pair is the quantity most often used. Sensitivity of the photoconductor is therefore proportional to $1/W$. $W$ has been measured by several investigators\textsuperscript{8,7} and a summary is given by Rowlands and DeCrescenzo\textsuperscript{9}. The generally accepted value of $W=50$ eV at $E=10^7$ V/m will be used for our calculations. Table 1 shows the typical exposure rates used in standard fluoroscopy (for catheter guidance) and cardiac cine fluoroscopy. The values are taken from deGroot\textsuperscript{5} for a 9" field of view and are scaled for 4.5", 6" and 12" field of view. The exposure rate is inversely proportional to the image area which means that the image in each case is formed from the same number of x-ray photons\textsuperscript{10,11}. This is done in practice, and causes the apparent noise (x-ray quantum noise) in the monitor image to be the same in each field of view.

<table>
<thead>
<tr>
<th>Field Size</th>
<th>Standard Fluoroscopy</th>
<th>Cardiac Cine</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5&quot;</td>
<td>120-240 $\mu$R/s</td>
<td>1200-1800 $\mu$R/s</td>
</tr>
<tr>
<td>6&quot;</td>
<td>67-135 $\mu$R/s</td>
<td>675-1012 $\mu$R/s</td>
</tr>
<tr>
<td>9&quot;</td>
<td>30-60 $\mu$R/s</td>
<td>300-450 $\mu$R/s</td>
</tr>
<tr>
<td>12&quot;</td>
<td>17-34 $\mu$R/s</td>
<td>169-253 $\mu$R/s</td>
</tr>
</tbody>
</table>

Table 1. Typical exposure rates used in standard and cardiac cine fluoroscopy as a function of field size

The signal current for an x-ray vidicon is given by:

$$i_s = \frac{X \eta \alpha A e e K \Psi}{W} \quad (1)$$

Where:

- $i_s$ = instantaneous signal current
- $X$ = input exposure rate
- $\eta$ = quantum efficiency
- $\alpha$ = photon fluence per roentgen ($2.8 \times 10^4$ x-ray/($\mu$R-cm$^2$))
- $A$ = area of x-ray absorption (circular)
- $\epsilon$ = average x-ray energy
- $e$ = elementary charge ($1.6 \times 10^{-19}$ C)
- $K$ = ratio of total to active scan time
- $\Psi$ = ratio of rectangular scan area to circular x-ray area
- $W$ = conversion efficiency (50 eV at $10^7$V/m)
The factor $\Psi$ accounts for the area of the circular x-ray field being different from the area scanned by the electron beam. Most XRII/TV systems display the circular image provided by the XRII (and circular x-ray field) within the rectangular area of the monitor. Similarly, the photoconductor of an x-ray vidicon can also be circular and displayed within a rectangular monitor. For comparison with an XRII/TV system, we assume a circular x-ray field, although a rectangular x-ray field could be assumed by setting $\Psi=1$. The signal that can be expected from a 9" x-ray vidicon with 500 $\mu$m a-Se at 90 kVp ($\varepsilon=47.5$ keV) and a standard fluoroscopic exposure rate of 30 $\mu$R/s has been calculated. A 525 line, 30 fps system is assumed which has the largest circular x-ray area that can fit into the rectangular scan area ($K=1.33$ and $\Psi=1.7$).

Then:

$$i_s = \left[30 \frac{\mu R}{s}\right] \times [0.52] \times \left[2.8 \times 10^4 \frac{x\text{-ray}}{\mu R \ cm^2}\right] \times \left[\pi \left(\frac{9 \times 2.54}{2}\right)^2 \ cm^2\right] \times \left[47.5 \times 10^3 \frac{eV}{x\text{-ray}}\right]$$

$$\times \left[1.6 \times 10^{-19} \frac{A \ s}{e}\right] \times [1.33] \times [1.7] \times \left[\frac{1e}{50 \ eV}\right] = 62 \ nA$$

Signal currents for an XRII/TV system range from 25 nA to 100 nA for a 30 $\mu$R/s exposure rate\textsuperscript{12,13,14,10}. Our calculated signal current of 62 nA is within this range and therefore should be adequate. It may seem counter-intuitive that an a-Se layer, which has no active amplification, is capable of producing approximately the same signal as an XRII/TV system which incorporates a high gain amplification stage. One must consider, however, that much of the gain provided by accelerating electrons in an XRII is used to compensate for other losses in the system such as light coupling at the input phosphor, photocathode inefficiency and light coupling from the output phosphor to the light sensitive photoconductor. One must also consider that one absorbed x-ray in the a-Se gives rise to $\sim1000$ electrons in comparison to $<1$ electron per light photon in a light sensitive vidicon.

**B) NOISE**

The purpose of an x-ray imaging system is to create a map or image of the x-ray transmission of the patient for the x-ray spectrum in use. The measured image, however, will always differ to some degree from the ideal transmission image. The ideal transmission image is referred to as the signal, and the difference between the ideal and measured image (error) is referred to as the noise. It is noise which limits our ability to distinguish between small differences in the ideal transmission or signal. Noise can never be totally eliminated and so we must be content to minimize it as much as possible.
Signal and noise have different forms at different points in the imaging chain. When x-rays pass through the patient the ideal transmission is approximated by the number of x-rays which exit the patient and arrive at the vidicon. Even at this early stage noise has already corrupted the ideal image in the form of statistical fluctuations in x-ray production and absorption called quantum noise and from x-ray scatter. At the a-Se layer the x-ray image is converted to a charge image which is further corrupted by statistical fluctuations in absorption and by variations in both the x-ray to electron conversion and dark current (both temporally and spatially).

Electron beam scanning converts the charge image on the a-Se surface to a signal current which must then be amplified. This electrical signal is prone to corruption by various forms of electrical noise such as amplifier noise, Johnson noise, shot noise, 1/f noise and external interference. The final video signal which is sent to a viewing monitor is usually where we evaluate signal and noise, however, some sources of noise are also associated with the viewing monitor such as glare and fixed patterns in the CRT phosphor coating.

Quantum noise is a fundamental noise associated with the use of x-rays and in an ideal system should represent the dominant noise source. A system dominated by quantum noise is referred to as quantum noise limited. Of the remaining sources the one which most seriously threatens quantum noise limited operation is amplifier noise. The various noise sources found in an x-ray vidicon will now be addressed.

1) Noise Sources

a) X-ray Quantum Noise

The number of x-rays (originating from an x-ray tube) which are absorbed per unit time in an a-Se layer is described by Poisson statistics\(^\text{15}\). According to Poisson statistics, if the average number of x-rays absorbed in a given time interval is \(N_{\text{abs}}\) then the variance in the number of x-rays absorbed in that same time interval \((\sigma_x^2)\) is also \(N_{\text{abs}}\). That is:

\[
\sigma_x^2 = N_{\text{abs}}, \quad \sigma_x = \sqrt{N_{\text{abs}}} \tag{3}
\]

\(\sigma_x\) is a fundamental noise that we must live with in our system. In order to compare noise sources, it is useful to reference all signals and noise to the current at the input of the preamplifier.
To calculate this noise we must first know the number of x-rays absorbed per pixel per frame.

\[ N_{abs} = Xa \alpha at_f \]  

(4)

Where: \( a \) = pixel area
\( t_f \) = time per frame

\( N_{abs}^{1/2} \) is thus the standard deviation or noise in the number of x-rays absorbed per pixel per frame. We then reference this to the preamplifier input (assuming MTF(\( f \))=1).

\[ \bar{I}_{nx} = \frac{\sqrt{N_{abs}} ee}{Wt_r} = \frac{\sqrt{Xa \alpha at_f ee}}{Wt_r} \]  

(5)

Where: \( \bar{I}_{nx} \) = rms noise current (instantaneous)
\( t_r \) = pixel readout time

Comparing this equation to that for signal current we find:

\[ \bar{I}_{nx} = \frac{i_s}{\sqrt{N_{abs}}} \]  

(6)

It is often convenient to express \( \bar{I}_{nx} \) in terms of \( i_s \) and bandwidth \( B \) using:

\[ B = \frac{1}{2t_r} \quad \text{and} \quad \Lambda K \psi = \frac{at_f}{t_r} \]  

(7)

Which gives:

\[ \bar{I}_{nx}(B) = \sqrt{\frac{2ei_s B e}{W}} \]  

(8)

The expression for \( B \) in Equation 7 is justified by the fact that the maximum noise frequency (\( B \)) we are interested in is the one which corresponds to the signal from successive pixels alternating high and low (high to low = 1 cycle in \( 2t_r \)).
Expressing Equation 8 as a spectral density $i_n(f)$ and including the modulation transfer function (MTF) from the input plane to the preamplifier input we have:

$$i_n(f) = \sqrt{\frac{2e^2\epsilon}{W}} \cdot MTF(f)$$

Where: $f =$ temporal frequency

$MTF(f)$ describes the blurring or averaging experienced by noise (or signal) as it passes from the input plane to the preamplifier. More specifically, $MTF(f) = M_{out}(f)/M_{in}(f)$ where $M_{out}(f)$ is the modulation at the output when a sine wave of frequency $f$ and modulation $M_{in}(f)$ is placed at the input. Modulation $M(f)$ (at the input or output) is defined as $M(f) = (S_1-S_2)/(S_1+S_2)$, where $S_1$ and $S_2$ ($S_1 > S_2 > 0$) are the maximum and minimum values of the sine wave respectively. In general the value $MTF(f)$ decreases with increasing $f$, that is high temporal and thus spatial frequencies are attenuated more greatly. Low values of $MTF(f)$ correspond to greater blurring or averaging and thus to reduced noise (or signal) at the preamplifier. X-ray quantum noise in an XRILL/TV referenced to the 1" vidicon target is given by a similar expression:

$$i_{n-\text{XRILL/TV}}(f) = \sqrt{2e^2\epsilon_2 g} \cdot MTF_{\text{XRILL/TV}}(f)$$

Where $g$ is the XRILL/TV gain in terms of the number of electrons produced in the 1" vidicon target per x-ray absorbed in the XRILL (~920 at 90 kVp).

Another noise source which is related to x-ray quantum noise is Swank noise. Swank noise is a statistical noise caused by fluctuations in x-ray absorption due to k-fluorescence escape. Swank noise is discussed later in relation to Detective Quantum Efficiency (DQE).

b) **X-ray Scatter**

X-ray scatter produces signal in unwanted locations on the target. X-ray scatter occurs in both the patient as well as parts of the imaging system. The input window, target substrate and other tube parts can all scatter x-rays onto the target. The spatial distribution of scatter contains predominantly low spatial
frequencies which produce a veiling glare and reduce contrast. The scatter image also has associated with it quantum noise. In a clinical fluoroscopic procedure 50-80%\textsuperscript{16} of the signal may be due to patient scatter (no grid) which can make x-ray scatter quantum noise the dominant noise source. Methods of reducing patient scatter such as grids\textsuperscript{17} are important since they not only improve contrast but reduce quantum noise.

c) **Johnson Noise**

Johnson noise or thermal noise is due to the random motion of carriers in a conductor. Johnson noise is characterized by a constant noise power within all resistive devices given by:

\[
P_J = \frac{\bar{v}_n^2}{R} = \bar{i}_n^2R = 4kTB
\]

Where:

- \(P_J\) = rms Johnson noise power
- \(\bar{v}_n\) = equivalent rms noise voltage
- \(\bar{i}_n\) = equivalent rms noise current
- \(k\) = \(1.38 \times 10^{-23}\) J/K
- \(T\) = temperature (300 K)
- \(R\) = resistance (\(\Omega\))
- \(B\) = bandwidth of measurement

Johnson noise is characterized as having a white or flat frequency spectrum and Gaussian amplitude distribution. Figures 3 and 4 show two common types of preamplifier circuits used in vidicons, the voltage preamplifier and the transimpedance preamplifier. The resistors of most concern with respect to Johnson noise are the bias resistor \((R_b)\) and the feedback resistor \((R_f)\). The rms Johnson noise current of either \(R_f\) or \(R_b\) referenced to the current at the input of the preamplifier is given by:

\[
\bar{i}_n(B) = \sqrt{\frac{4kTB}{R}}
\]

Where: \(R\) = either \(R_b\) or \(R_f\)

And in terms of spectral density:

\[
i_n(f) = \sqrt{\frac{4kT}{R}}
\]

From these expressions we can see that it is desirable to have both \(R_b\) and \(R_f\) as large as possible. There are practical limits to how large \(R_b\) and \(R_f\) can be. If \(R_b\) is too large, a significant voltage drop will appear across it during bright scenes resulting in a drop in target potential. A common value of \(R_b\) used
Figure 3. Voltage preamplifier with hi-peaker frequency compensation. See text for explanation of components and variables.

Figure 4. Transimpedance Amplifier. See text for explanation of components and variables.
in 1" vidicon preamplifiers is $R_g = 1 \, \text{M}\Omega$ which is also suitable for a large area vidicon. $R_g = 1 \, \text{M}\Omega$ corresponds to a Johnson noise of 0.28 nA rms for a 5 MHz bandwidth. In a transimpedance preamplifier, $R_p$ is the feedback resistor which determines the gain of the preamplifier. If $R_p$ is too large, however, the parasitic capacitance of $R_p$ (~0.1 pF) and the stray capacitance at the preamplifier input can cause the gain at high frequencies to drop. Most preamplifiers have $R_p \approx 500 \, \text{k}\Omega$ and a Johnson noise of 0.4 nA rms (5 MHz). A transimpedance preamplifier with resistors $R_b$ and $R_F$ has in general a higher level of Johnson noise than a voltage preamplifier with only $R_b$. This difference may be unimportant, however, if Johnson noise is negligible with respect to other noise sources.

**d) Shot Noise**

Shot noise occurs whenever there is electrical current flow and is due to the discrete nature of the charges which compose the current. Shot noise is in effect quantum noise of electrons. The rms shot noise current ($\overline{i_n(B)}$) and shot noise current spectral density ($i_n(f)$) are given by:

$$\overline{i_n(B)} = \sqrt{2eI_B}, \quad i_n(f) = \sqrt{2eI_s} \tag{14}$$

Shot noise is Gaussian distributed in amplitude and has a white frequency spectrum. Typical values of $\overline{i_n(B)}$ for a vidicon are given in Table 3.

<table>
<thead>
<tr>
<th>Signal Level ($i_s$) [nA]</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot Noise ($\overline{i_n(5 MHz)}$) [nA rms]</td>
<td>0.04</td>
<td>0.13</td>
<td>0.4</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 3. Electron shot noise $\overline{i_n(B)}$ in a 5 MHz bandwidth calculated using Equation 14 for different signal currents typical of a vidicon.

From Table 3 it can be seen that shot noise will exceed Johnson noise for signals of ~100 nA or more and becomes comparable to amplifier noise (to be discussed later) only for signals of the order of 1000 nA which is close to the maximum beam current.

The expressions for electron shot noise and quantum noise differ only by the terms $e/W$ for the x-ray vidicon and by $g$ for the XRII/TV. Since $e/W$ and $g$ are large, electron shot noise is negligible in comparison to x-ray quantum noise. An exception to this can occur at high spatial frequencies where the MTF that transfers quantum noise to the target is very low. Another exception occurs if $e/W$ or $g$ are purposely made low, such as for digital subtraction angiography (DSA).
Another possible source of shot noise is that produced by dark current. While a DC level can be subtracted from the target current, subtraction of the dark current shot noise is not possible and must be lived with. Fortunately, $\alpha$-Se has a very low dark current. For a large area vidicon (9") a dark current of less than 30 nA is achievable (see Chapter 5). This level of dark current corresponds to 0.22 nA rms dark current noise in 5 MHz which is less than other noise sources. For normal operating conditions therefore, electron shot noise in an x-ray vidicon can be ignored.

e) $1/f$ Noise

$1/f$ noise is a type of noise found in real devices such as resistors and transistors and has a spectral power density which is proportional to $1/f$. $1/f$ noise varies depending on the process by which the resistor or transistor was made. Although a complete explanation for $1/f$ noise has yet to be found, it is known that $1/f$ noise in field effect transistors is related to trapping effects at the semiconductor surface\textsuperscript{18,19}. Fortunately it becomes negligible above a certain frequency. For the Junction Field Effect Transistor (JFET) used in preamplifiers, $1/f$ noise is usually negligible above $\sim$100 Hz. In a vidicon television camera the output is clamped to a fixed level at the beginning of each line. During clamping the beam is turned off so that the amplifier sees a true zero signal. This has the advantage of eliminating noise at frequencies below the clamping (i.e. line) rate. Since line rates are typically 15 kHz or more on 30 fps systems the $1/f$ noise is effectively eliminated\textsuperscript{20}.

f) Amplifier Noise

The small current signal produced at the target of a vidicon must be electronically amplified to the level of a standard video signal. A vidicon contains a chain of amplifiers of which the first is called the preamplifier. Because the preamplifier is where the signal is the smallest, it is also where it is most susceptible to the addition of noise. The first transistor in the preamplifier is the dominant source of amplifier noise relative to the signal and its selection is therefore most critical. At the present time, the lowest noise device available for high input impedance amplification is the Si JFET transistor and it is used almost universally in modern vidicon preamplifiers. A high impedance amplifier is chosen because it minimizes Johnson noise\textsuperscript{31}.

The amplifier noise associated with the JFET is actually due to internal effects such as: shot noise of the gate leakage; thermal noise of the channel resistance; thermal noise of the channel capacitively coupled to the gate; generation-recombination noise; and $1/f$ noise. All of these effects contribute to the JFET's
total amplifier noise which is referenced to the JFET's input (gate) for convenience. The equivalent noise model for a JFET has both a noise voltage source in series with the gate as well as a noise current source shunting the gate. For the high impedance source and frequency range used by vidicons, the current noise of the JFET can be ignored. Another type of the FET called a MOSFET (Metal Oxide Semi-Conductor Field Effect Transistor) also has a high impedance input however it has a larger value of noise voltage in comparison to a JFET. Bipolar transistors can be found with lower noise voltage than JFETs however their current noise is much higher due to their non-negligible base current.

Since the internal workings of the JFET transistor are beyond our control we can only choose from the best available transistors. The transistor with the lowest absolute noise will not necessarily be the one that produces the lowest noise in the preamplifier. The choice is complicated by gate capacitance and other factors. There are two main types of preamplifier configuration\(^\text{10}\). They are:

A) Voltage amplifier with hi-peaker frequency compensation  
B) Transimpeance amplifier

These two configurations are shown in Figures 3 and 4. In a voltage amplifier configuration the signal current \((i_s)\) produces a signal voltage across the bias resistor \(R_b\) which is then amplified. The presence of stray capacitance at the input such as \(C_r\) (tube), \(C_w\) (wiring), and \(C_f\) (JFET) shunt the signal at high frequencies and a frequency compensation circuit or "hi-peaker" is required. The transimpeance amplifier eliminates the need for extra frequency compensation by using feedback. Feedback makes the input to the preamplifier a virtual ground and all the signal current will therefore flow into the preamplifier input. The signal current flows through \(R_F\) and therefore the current to voltage gain is \(R_F\) itself.

Some preamplifiers use a hybrid design which includes a transimpeance configuration and some added frequency compensation. In such a design, \(R_F\) is chosen large to reduce Johnson noise but the stray capacitance of \(R_F\) and stray capacitance at the input interferes with feedback at high frequencies and so some frequency compensation is needed. Alternatively, frequency compensation is sometimes incorporated into the transimpeance amplifier feedback path\(^\text{22}\). This is done to compensate for the stray capacitance of \(R_F\) which allows larger values of \(R_F\) to be used while eliminating the post hi-peaker circuit.

In both amplifier configurations either a frequency compensation circuit or feedback is used to obtain a flat frequency transfer for the signal. Unfortunately the techniques which provide a flat signal transfer have a detrimental effect on noise. In each amplifier configuration the amplifier noise is modelled as \(e_n\).
at the input which is an equivalent noise voltage spectral density. The value $e_n$ has flat (white) spectrum in the frequency range of interest (15 kHz to 15 MHz). This white noise spectrum becomes frequency compensated along with the signal to produce a noise spectrum that increases with frequency. Each preamplifier configuration has its advantages and disadvantages, but interestingly, all produce the same amplifier noise characteristic. Amplifier noise due to $e_n$ reference to the input is given by:

$$S = i^2_{in}(f) = \frac{e^2_n}{R^2} + 4\pi^2 e^2_n C_s^2 f^2$$  \hspace{1cm} (15)

Where:

- $S$ = noise power spectral density
- $i_{in}(f)$ = equivalent noise current spectral density at preamplifier input
- $R$ = $R_f$ for a transimpedance amplifier, $R_b$ for voltage amplifier
- $e_n$ = JFET noise voltage spectral density
- $C_s$ = $C_T + C_w + C_F$ = input stray capacitance
- $f$ = temporal frequency

The first term in Equation 15 represents the amplifier noise voltage $e_n$ passed on to the output unamplified. This term is negligible when compared to Johnson and shot noise and can be ignored. The second term shows a noise power which increases with frequency. Because of its shape, it is often called a triangular noise spectrum$^{20,23,24}$. At high frequencies this noise easily exceeds Johnson noise. It is the location of $e_n$ within the circuit which causes high frequency noise (but not high frequency signals) to be boosted.

If Equation 15 is integrated over the bandwidth $B$ we get an expression for the total rms amplifier noise ($\bar{i}_{in}(B)$).

$$\bar{i}_{in}(B) = \sqrt{\int_0^B 4\pi^2 e^2_n C_s^2 f^2 \, df} = \sqrt{\frac{4}{3} \pi^2 e^2_n C_s^2 B^3}$$  \hspace{1cm} (16)

Equations 15 and 16 show the importance of keeping the stray capacitance as low as possible. The stray capacitance of the vidicon tube $C_T$ depends on the proximity of the target electrode other electrodes including meshes in the tube. The wiring capacitance $C_w$ is the capacitance of the connection between the tube and the preamplifier. This is minimized by having the preamplifier in close proximity to the tube. The FET input capacitance $C_F$ is inherent to the transistor used and for a given value of $e_n$ the lowest $C_F$ would be desirable.
It is the nature of JFET technology however, that \( C_F \) and \( e_n \) are coupled parameters\(^{20} \) with:

\[
\frac{e_n}{\sqrt{C_F}} = K
\]

(17)

Where: \( K = \) a constant

If we substitute Equation 17 into Equation 16 and solve for minimum noise we find that minimum noise occurs when \( C_F \) is made equal to \( (C_T+C_W) \).

\[
\bar{I}_{\text{ma}}(B) = \sqrt{\frac{4}{3} \pi^2 \left( \frac{K^2}{C_F} \right)^3 (C_T+C_W+C_F)^2 B^3}
\]

(18)

\[
\frac{d\bar{I}_{\text{ma}}(B)}{dC_F} = 0 = \frac{4}{3} \pi^2 K^2 B^3 \left[ \frac{2(C_T+C_W+C_F)}{C_F} - \frac{(C_T+C_W+C_F)^2}{C_F^2} \right]
\]

(19)

\[
C_F = C_T + C_W
\]

(20)

Thus to summarize the procedure for obtaining the lowest amplifier noise: 1. Reduce \( C_T \) and \( C_W \) as much as possible; and 2. Choose a JFET with \( C_F=C_T+C_W \) and \( e_n \) that minimizes the value \( e_nC_F \). If a single JFET with \( C_F=C_T+C_W \) is not available JFETs can be paralleled to increase \( C_F \). Putting \( N \) JFETs in parallel will increase \( C_F \) by \( N \) times and reduce \( e_n \) by \( N^{1/2} \). By comparison with Equation 17, it is apparent that paralleling JFETs is approximately equivalent to using a single JFET of the same total capacitance. The value of \( e_n \) for a particular JFET depends strongly on the process geometry by which the transistor was made. Data sheets usually give the value of \( e_n \) versus frequency for a particular process geometry. \( e_n \) depends also on how the JFET is biased. For lowest \( e_n \) one should use the highest bias possible without significantly heating the device as \( e_n \) also increases with temperature. Assuming typical values for a 1" vidicon preamplifier of \( C_T=10 \) pF, \( C_W=2 \) pF, \( C_F=12 \) pF, \( e_n=1.2 \) nV/(Hz)\(^{1/2} \) and \( B=5 \) MHz we find \( \bar{I}_{\text{ma}}(B)=1.2 \) nA rms. This is close to the value found in optical vidicon cameras. For a large area x-ray sensitive vidicon, target capacitance \( C_T \) will be larger than that of a 1" vidicon. If we assume that \( C_T \) increases proportionally with tube area, then a 9" vidicon would have ~81 times the capacity, thus greatly increasing the noise. This, fortunately, does not have to be the case. The dominant source of capacitance in a large area vidicon is the target to mesh capacitance which is in effect a parallel plate capacitor. When the vidicon is increased from 1" to 9", the mesh can be moved back by a factor of 9 while retaining the same number of lines of resolution. Capacitance of the tube is therefore only a factor of 9 larger.
Assuming that the 9" vidicon was connected to the preamplifier of the 1" vidicon, the stray capacity \( C_s \) would increase by a factor of \((9+1)/(1+1)=5\) and thus noise would increase by a factor of 5. However, the lowest noise occurs when we match the amplifier input capacitance to the tube capacitance. By paralleling JFETs to achieve the desired \( C_f \) total, the resulting amplifier would then have a noise of only \((9)^{1/2}\) or 3 times the 1" vidicon.

In summary, the relationships between x-ray vidicon amplifier noise and tube diameter \( d \) are as follows:

1) For a constant number of lines of resolution;

\[
C_T \propto d
\]  

2) Using an unmodified 1" vidicon preamplifier \( (\varepsilon_a=\text{const}) \);

\[
\overline{\overline{I_{na}}}(B) \propto (C_T + \text{const.})
\]  

3) Using a preamplifier with matched capacitance;

\[
\overline{\overline{I_{na}}}(B) \propto \sqrt{C_T} \propto \sqrt{d}
\]

The above analysis assumes that the large area vidicon is a scaled version of a 1" vidicon with respect to stray capacitance. In practice, 1" vidicons are available in standard and Low Output Capacitance (LOC) versions. The LOC vidicon has a reduced target to mesh capacitance \( C_M \) as compared to a standard 1" vidicon, and its target to housing capacitance \( C_H \) is also lower \( (C_T=C_M+C_H) \). This is achieved by reducing the target electrode area to match the imaging area and by making connection to the electrode via a pin in the faceplate\(^{25}\). It is therefore desirable that a large area vidicon should be a scaled version of the LOC 1" vidicon. Figure 5 shows the design features of a large area vidicon that minimizes stray capacitance. These are: 1) A target electrode area that matches the imaging area; 2) A large target electrode to housing distance; and 3) A low capacitance feedthrough to the preamplifier.

In addition to a field mesh the large area vidicon may also contain a suppressor mesh to ensure electrical stability of the target surface potential. The suppressor mesh, being closer to the target, increases the value of \( C_M \). It is desirable, therefore, that the suppressor mesh be as far from the target as possible, or ideally, be non-existent. The suppressor mesh and methods of achieving stability without its presence are discussed in Chapter 4.
Figure 5. X-ray vidicon design for low stray capacitance.

\[ C_T = C_H + C_M \]

Figure 6. MTF used in noise calculations.
g) **External Noise**

External noise although not a fundamental noise source is nevertheless a very real and troublesome type of noise. The preamplifier is the circuit most prone to external interference. Common sources of external noise in an x-ray vidicon are:

1. 60 Hz and Radio Frequency Interference (RFI) on the target
2. 60 Hz and RFI in the power supply
3. Horizontal deflection pickup
4. High Voltage breakdown

The target in the open is an antenna for 60 Hz and RFI in the air. The target, bias circuitry, and preamplifier all need to be shielded by metal enclosures. Shielding of the target can be by means of a metal shroud external to the tube. Connections to the field mesh and suppressor mesh must be properly filtered and Radio Frequency (RF) bypassed at the tube shield before they enter the tube. This is necessary since the meshes are capacitively coupled to the target. If separate enclosures are used for the tube, bias and preamplifier, then good grounding must be maintained between them. Power supply connections into the bias circuit and preamplifier must be filtered and RF bypassed as they enter the enclosure or enclosures. Even though the preamplifier itself may be immune to noise on the power supply, without filtering and RF bypassing at the enclosure, the noise can radiate from the power supply wire inside the box to the target input.

The horizontal deflection circuit uses large potentials (100 V) and fairly large current (1 A) pulses ~5 μs wide in order to drive the horizontal deflection coil. These pulses are notorious for radiating RFI energy and producing power supply noise. While shielding to keep RFI and power supply noise out of the preamplifier exists, no shielding is completely effective. Further precautions should be taken to prevent the horizontal circuit from radiating RFI and corrupting the power supply. Shielding the horizontal deflection circuit and yoke connections are recommended as well as filtering its power supply. Also since the deflection yoke is magnetic it can induce eddy currents in nearby conductors. Power supply and signal conductors must be kept away from the yoke. Horizontal deflection pickup is easily recognized as vertical lines on the television screen usually on the left side. Their suppression, however, can be quite challenging.

Since the x-ray vidicon uses large target voltages a problem with high voltage breakdown can occur on the target connection. Teflon insulators are recommended for low leakage and breakdown resistance. Just
as important as the insulator material however, is the cleanliness of the insulator surface. Surface contamination causes a breakdown along the surface known as tracking. Insulator breakdown is characterized by short duration pulses in the video which look like short white horizontal streaks in the picture. The frequency of pulses will increase with potential and at a fixed potential will be most frequent when the potential is first applied. With proper cleaning of insulators however, high potential breakdown noise can be virtually eliminated.

h) **Image Artifacts**

Artifacts are any unwanted signals of a non-random nature which appear in the image. Artifacts can come from an external source such as horizontal deflection pickup mentioned earlier or it can occur within the tube itself.

Sources of artifacts originating from within the tube are:

1. *a-Se Defects*
2. *Mesh Beat*

The most common type of *a-Se* defect is the "white spot" or conduction spot. These are microscopic regions of high conduction in the *a-Se* layer. The spot itself is seldom larger than the electron beam width and will usually only show up on 1 or 2 lines which scan the spot. Spots with high conduction can cause beam pulling toward the spot which makes the spot appear larger than it is. Contamination of the substrate surface before *a-Se* evaporation and contamination of the *a-Se* surface afterwards can lead to white spots. Elimination of *a-Se* defects requires rigorously clean processing and handling techniques. If any spots are present, their small size allows them to be masked fairly well. Substitution of an adjacent pixel or an average of adjacent pixels could be done easily in some post processing stage. White spots are further discussed in Chapter 5.

Mesh beat is a regular pattern of lines in two perpendicular directions which originates from the passage of the electron beam through the field mesh and suppressor mesh. The pattern may occur due to moire or spatial beat frequency between the scanning raster and one mesh, or between two meshes. Mesh beat can be reduced by placing one mesh at some angle with respect to the other mesh. These meshes should also be placed at some angle with respect to the raster. Using a mesh with a finer pitch will help but finer meshes have a reduced transparency. The state of the art in meshes is about 2000 holes per inch with 45% transparency which is more than adequate for a large area vidicon. One should also strive to keep the *a-Se* to suppressor mesh spacing as large as possible so that the mesh will be out of focus. Vibration of the mesh can also modulate the target signal. Having a taut mesh will help to reduce low frequency
vibration which is the most irritating. Mesh selection and placement is discussed further in Chapter 3.

While the x-ray vidicon is prone to artifacts of its own it is free of the largest source of structural noise found in an XRII/TV system, namely the granularity of the input and output phosphors.\textsuperscript{26} Evaporated a-Se layers are solid layers of homogeneous composition and a high degree of thickness uniformity and if free of white spots exhibit a structural uniformity which is much better than that of the phosphor of the XRII/TV system. Uniformity of the Sb\textsubscript{2}S\textsubscript{3} layer (applied to the a-Se surface to reduce secondary electron emission) is also known to be quite good from its use in 1" light sensitive vidicons.

Overall in a properly designed x-ray vidicon it should be possible to eliminate mesh beat completely. Elimination of white spots in the a-Se will be the most difficult to achieve, however, once achieved the a-Se target should exhibit a greatly reduced structural background compared to the XRII.

2) \textbf{Comparison of X-Ray Vidicon Noise Sources}

The relative contributions of x-ray quantum noise, Johnson noise and amplifier noise in the x-ray vidicon and XRII/TV will be compared. Two specific cases will be considered which will be referred to as Standard Fluoroscopy and Cardiac Cine and are defined in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>Standard Fluoroscopy</th>
<th>Cardiac Cine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of field of view</td>
<td>9&quot;</td>
<td>4.5&quot;</td>
</tr>
<tr>
<td>Number of video lines</td>
<td>525 (482 active)</td>
<td>1023 (940 active)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5 MHz</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Frame rate</td>
<td>30 fps</td>
<td>30 fps</td>
</tr>
<tr>
<td>Average exposure rate</td>
<td>$X_{\text{avg}} = 30 \mu R/s$</td>
<td>$X_{\text{avg}} = 1200 \mu R/s$</td>
</tr>
<tr>
<td>Minimum exposure rate</td>
<td>1/10 $X_{\text{avg}}$</td>
<td>1/10 $X_{\text{avg}}$</td>
</tr>
<tr>
<td>Maximum exposure rate</td>
<td>10 $X_{\text{avg}}$</td>
<td>3 $X_{\text{avg}}$</td>
</tr>
</tbody>
</table>

Table 3. Two cases used to compare large area x-ray vidicon noise sources. $X_{\text{avg}}$ is the mean exposure rate at the input of the device.

These two cases represent the two extremes found in real time (30 fps) fluoroscopy. Standard Fluoroscopy is the low exposure rate, small signal, low resolution extreme used for catheter guidance, while Cardiac
Cine is the high exposure rate, large signal, high resolution extreme used during coronary contrast injection. The range of exposure rates used are chosen to match those found in modern XRII/TV systems. In Standard Fluoroscopy, the range of exposure rate at the XRII input is between $1/10X_{\text{avg}}$ and $10X_{\text{avg}}$ where $X_{\text{avg}}$ is the mean exposure rate. Then, XRII/TV signal currents for $1/10X_{\text{avg}}$, $X_{\text{avg}}$ and $10X_{\text{avg}}$ correspond to $i_s \approx 8, 80$ and $800$ nA respectively while x-ray vidicon signal currents are $6.2$, $62$ and $620$ nA respectively.

For Cardiac Cine $X_{\text{avg}}=1200$ µR/s for which the XRII/TV system is adjusted (using an optical aperture) to $i_s \approx 600$ nA. Since the maximum beam current in a 1" vidicon is $\sim 2000$ nA, the maximum exposure rate is only $\sim 3X_{\text{avg}}$. (Although an upper limit of $10X_{\text{avg}}$ is desirable a compromise of $3X_{\text{avg}}$ is used in order to maximize SNR at $X_{\text{avg}}$). Cardiac Cine signal currents can then be taken to be $62$, $620$ and $1860$ nA for both the XRII/TV and x-ray vidicon.

In order to reference quantum noise to the preamplifier input, the MTF from the incident x-ray image to the preamplifier input ($MTF(f)$) is required. We assume that the $MTF(f)$ of the x-ray vidicon is determined mainly by the aperture of the beam spot which can be approximated by a cosine-squared distribution$^{12}$. The MTF for the beam profile which is the Fourier transform of Equation 24 is given by:

$$J(r) = J_0 \cos^2 \left( \frac{\pi r}{4r'} \right) \quad \text{for} \quad |r| \leq 2r' $$$$
= 0 \quad \text{for} \quad |r| > 2r' $$

Where:

- $J(r)$ = current density
- $r$ = radius
- $r'$ = FWHM radius
- $J_0$ = constant of proportionality

In Equation 24:

$$MTF(f) = \frac{\sin 4\pi r' f_s}{4\pi r' f_s (1 - (4r' f_s)^2)} $$

Where:

- $f_s$ = spatial frequency
Since electronic noises are expressed in terms of temporal frequency, we require the relationship between spatial frequency \( f_s \) and temporal frequency \( f \) which are:

\[
f_s = \frac{f}{t_H} \quad \text{and} \quad t_H = \frac{4}{3} d_i
\]  

(26)

Where:  
- \( t_H \) = active horizontal scan time  
- \( l_H \) = picture width  
- \( d_i \) = image diameter

The measured MTF of actual 1" light sensitive vidicons shows Equation 25 to be a good approximation\(^2\). Since the x-ray vidicon is a scaled version of a 1" vidicon, the same relative MTF can be expected. The theoretical x-ray vidicon MTF is plotted in Figure 6 for both a 9", 525 line (Standard Fluoroscopy) mode, as well as a 4.5", 1000 line (Cardiac Cine) mode. For the XRII/TV, the MTF as given by deGroot\(^3\) was used and is also shown in Figure 6. Details concerning the x-ray vidicon and XRII/TV MTFs are discussed further in Chapter 3. The factors \( e, W, g, K \) and \( \Psi \) are the same as those used in the calculation of signal. The value of \( R_F \) used was \( R_F=500 \text{ k} \Omega \). The values of \( e_n \) and \( C_S \) are given in Table 4 for a standard 1" vidicon, a low output capacitance 1" vidicon, a 9" x-ray vidicon with suppressor mesh, and a 9" x-ray vidicon without suppressor mesh. The capacitance components \( C_p, C_w \) and \( C_f \) which add to form \( C_S \) are also given in Table 4 along with justification.

First, the spectral noise densities \( i_{x}\), \( i_{na} \) and \( i_{nj} \) for the Standard Fluoroscopy case in both the large area x-ray vidicon (Figure 7) and the XRII/TV (Figure 8) will be compared. At low spatial frequencies, x-ray quantum noise is clearly dominant in both systems. At spatial frequencies above 0.3 lp/mm, the MTF causes quantum noise to be reduced in both systems. In a light sensitive vidicon, Johnson noise is the dominant noise source at low frequencies. Figure 7 and Figure 8 show, however, that Johnson noise is negligible in comparison to quantum noise in an x-ray vidicon or XRII/TV system. The electronic noise of most concern is amplifier noise. For the XRII/TV, amplifier noise exceeds x-ray quantum noise only in the region where horizontal resolution exceeds vertical resolution. The use of a low output capacitance vidicon offers some advantage at those high spatial frequencies. In the large area x-ray vidicon, however, amplifier noise is larger, because of its larger stray capacitance, and can exceed quantum noise in the dark parts of the image near the point of equal resolution. The elimination of the suppressor mesh would greatly improve this situation.

Spectral noise densities for the Cardiac Cine case are shown in Figure 9 for the large area x-ray vidicon and in Figure 10 for the XRII/TV. The curves are similar to those of the Standard Fluoroscopy case.
except that the MTF of the XRII/TV has a much stronger influence on x-ray quantum noise. For the XRII/TV, amplifier noise exceeds quantum noise at lower spatial frequencies than for the x-ray vidicon. For Cardiac Cine, the large area vidicon, therefore, has superior noise properties in comparison to the XRII/TV.

<table>
<thead>
<tr>
<th></th>
<th>Normal 1&quot; vidicon</th>
<th>LOC(a) 1&quot; vidicon</th>
<th>9&quot; vidicon with suppressor mesh(b)</th>
<th>9&quot; vidicon without suppressor mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_M$</td>
<td>4.5 pF(c)</td>
<td>2.0 pF(c)</td>
<td>60 pF(d)</td>
<td>12 pF(e)</td>
</tr>
<tr>
<td>$C_H$</td>
<td>3.0 pF(c)</td>
<td>2.0 pF(c)</td>
<td>6 pF(f)</td>
<td>6 pF(f)</td>
</tr>
<tr>
<td>$C_T = C_M + C_H$</td>
<td>7.5 pF(g)</td>
<td>4.0 pF(g)</td>
<td>66 pF</td>
<td>18 pF</td>
</tr>
<tr>
<td>$C_W$</td>
<td>3.0 pF</td>
<td>3.0 pF</td>
<td>3 pF(g)</td>
<td>3 pF(g)</td>
</tr>
<tr>
<td>Total JFET $C_F$</td>
<td>10.5 pF</td>
<td>7.0 pF</td>
<td>69 pF</td>
<td>21 pF</td>
</tr>
<tr>
<td>$C_S = C_T + C_W + C_F$</td>
<td>21 pF</td>
<td>14 pF</td>
<td>138 pF</td>
<td>42 pF</td>
</tr>
<tr>
<td>Total amplifier noise in 5 MHz(0)</td>
<td>0.83 nA rms</td>
<td>0.68 nA rms</td>
<td>2.13 nA rms</td>
<td>1.2 nA rms</td>
</tr>
</tbody>
</table>

(a) LOC - Low Output Capacitance  
(b) Suppressor mesh at 140 V shown to be stable when porous Sb$_2$S$_3$ used  
(c) Values taken from Franken$^{25}$  
(d) Suppressor mesh at 6 mm, 140V  
(e) Field mesh at 30 mm, 700V  
(f) Target to x-ray window, 6 cm average  
(g) Target to amplifier distance same as 1" vidicon  
(h) Based on Siliconix J309, 7 pF, 1.2 nV/(Hz)$^{0.5}$  
(i) $i_{na}(B)$ See Equation 16

Table 4. Capacitance components used in amplifier noise calculation for both the 1" light sensitive vidicon of an XRII/TV system and a 9" x-ray vidicon.

Figures 7, 8, 9 and 10 show that Johnson noise is negligible compared to x-ray quantum noise at all exposure rates and frequencies of interest. The requirement of making $R_s$ and $R_f$ large is, therefore, relaxed, which aids in preamplifier design.

3) **Noise Perception**

   a) **The Triangular Noise Spectrum**

   The electronic noise in a video signal is not flat (white) but rather its spectral density increases with increasing frequency. This, we saw earlier, is a result of the video amplifier compensating for the
Figure 7. X-ray Vidicon spectral noise density components for Standard Fluoroscopy mode (9", 525 lines).

Figure 8. XRII/TV spectral noise density components for Standard Fluoroscopy mode (9", 525 lines).
Figure 9. X-ray Vidicon spectral noise density components for Cardiac Cine mode (4.5", 1000 lines).

Figure 10. XRII/TV spectral noise density components for Cardiac Cine mode (4.5", 1000 lines).
shunting effect of stray capacitance at the input. Because of the characteristic shape of the amplifier noise curve this type of noise has been called triangular. Since television scanning is in the horizontal direction, noise horizontally will have a triangular spectrum while noise in the vertical direction is flat or white.

Since the dominant source of noise in both the x-ray vidicon and XRJ/TV systems is amplifier noise, it is important to understand how differences in this predominantly high frequency noise will be perceived. Noise at different temporal frequencies has a different appearance to the viewer. According to Hall\textsuperscript{20} low temporal frequency noise in a television system appears as horizontal streaks, medium frequency noise appears as "snow" while high frequency noise appears as dancing scintillations. It has been found that the appearance of high frequency triangular noise is much less objectionable than white noise of equal power\textsuperscript{28,29,30}. While triangular noise may be perceived to be less irritating\textsuperscript{21}, Frame has found that "The detection threshold signal to noise ratio was experimentally found to be higher (i.e. lower performance) for the noise spectrum associated with vidicon type devices than for white noise with a flat spectrum". In his experiment, an adjustable low contrast bar pattern was viewed against a white background. For large spatial frequencies he found that a higher contrast was needed for detection when the noise was triangular instead of white.

Overall our perception of noise is greater at low frequencies making high frequency triangular noise less objectionable than white noise of equal power, however, triangular noise does reduce detection ability over white noise of equal power when high frequencies are important to the detection task.

**b) Noise and Lag**

Up to this point we have dealt with the magnitude of noise that is present in 1 frame of a video sequence. It is well known however, that our eye and brain integrates consecutive frames in forming our perception. According to Schade, the number of frames integrated is about three\textsuperscript{24}. Others use a value from three to six\textsuperscript{12}. Integration by the eye of \(N\) frames reduces noise by a factor of \(N^{1/2}\) and results in a lower perceived noise than that of a single frame. In an XRJ/TV system temporal lag mostly due to the light sensitive vidicon is also responsible for some noise reduction. The amount of lag depends greatly on the type of vidicon tube employed. For procedures with rapidly moving objects lag is objectionable as it hinders visualization. In other procedures with slower moving objects, however, some lag is welcomed because of its beneficial effect on noise\textsuperscript{31,32,14}. Some manufacturers produce light sensitive vidicons for medical use which have a reduced photoconductor thickness in order to increase lag and reduce quantum noise on the fluoroscopic image\textsuperscript{33}. One manufacturer produces a vidicon with adjustable lag and noise reduction.
In this case lag is controlled by the amount of bias light used.

A more flexible method of controlling lag is to use a low lag imaging tube and post process the images with the algorithm of ones’ choice. Complex algorithms which adapt to image brightness, motion content and user inputs are possible. The large area vidicon with an amorphous a-Se photoconductor should be a low lag device allowing this type of lag control. (See Chapter 3)

C) SIGNAL TO NOISE RATIO: SNR

The $SNR(f)$ or frequency dependent SNR of our system is defined by:

$$SNR(f) = \frac{i_{\text{MTF}}(f)}{\sqrt{i_{\text{MTF}}(f)^2 + i_{\text{MTF}}(f)^2 + i_{\text{MTF}}(f)^2 + i_{\text{MTF}}(f)^2}}$$

If we substitute Equations 9,13,14 and 15 into Equation 27 we obtain the SNR for the x-ray vidicon ($SNR_{\text{vid}}(f)$) given by:

$$SNR_{\text{vid}}(f) = \frac{i_{\text{MTF}}(f)}{\sqrt{2ei_{\text{MTF}}M_{\text{MTF}}^2(f) + \frac{4kT}{R} + 2ei_{\text{MTF}} + 4\pi^2e^2C^2f^2}}$$

If we substitute Equations 10, 13, 14 and 15 into Equation 27, we obtain the SNR for the XRII/TV system given by:

$$SNR_{\text{XRII/TV}}(f) = \frac{i_{\text{MTF}} M_{\text{MTF}}^2(f)}{\sqrt{2ei_{\text{MTF}} M_{\text{MTF}}^2(f) + \frac{4kT}{R} + 2ei_{\text{MTF}} + 4\pi^2e^2C^2f^2}}$$

$SNR(f)$ for the Standard Fluoroscopy case is shown in Figure 11 for both the large area x-ray vidicon and the XRII/TV. To these graphs, are also added lines (dotted) which represent the Rose threshold for detectability. This is a line below which the noise will be too large compared to the signal for the signal to be detected.
Figure 11. SNR(f) for the X-ray Vidicon and XRIL/TV in Standard Fluoroscopy mode (9", 525 lines).

Figure 12. SNR(f) for the X-ray Vidicon and XRIL/TV in Cardiac Cine mode (4.5", 1000 lines).
According to Rose, the SNR at the eye required to detect an object must be above -5, i.e.:

\[
\text{SNR}_{\text{OBJ,EYE}} > 5 \quad (30)
\]

Since the eye integrates approximately 4 video frames during visualization, the SNR per frame is therefore:

\[
\text{SNR}_{\text{OBJ,FRAME}} > \frac{5}{\sqrt{4}} \quad (31)
\]

In relating the above SNR with the \( \text{SNR}(f) \) of our graph, there is a problem since \( \text{SNR}(f) \) refers to the SNR spectral density on one horizontal line while \( \text{SNR}_{\text{OBJ,FRAME}} \) refers to the total SNR for all frequencies related to an object area that may span many horizontal lines.

To resolve this, consider a square object of dimension \( d \) on each side. The bandwidth \( B \) required to reproduce this object is given by:

\[
B = \frac{1}{2t_d} \quad (32)
\]

Where: \( t_d \) = time for beam to pass horizontally across the object

Additional relations that relate \( t_d \) to \( d \) in a raster scanned system are:

\[
\frac{d}{l_H} = \frac{t_d}{t_H} \quad , \quad \frac{d}{l_V} = \frac{n_d}{n_V} \quad , \quad \frac{l_H}{l_V} = \frac{4}{3} \quad (33)
\]

Where:
- \( l_H \) = horizontal width of raster scan
- \( t_H \) = active horizontal scan time (52 \( \mu \)s in RS-170)
- \( l_V \) = vertical height of raster scan
- \( n_d \) = number of scan lines occupied by the object
- \( n_V \) = total number of active vertical scan lines (483 in RS-170)

Combining Equation 32 with Equation 33, we obtain an expression for \( B \) in terms of the number of horizontal lines that pass through the object \( (n_d) \) and other constants of the television system:

\[
B = \frac{B_0}{n_d} \quad \text{where} \quad B_0 = \frac{2n_V}{3t_H} \quad (34)
\]

Where: \( B_0 \) = Bandwidth required for an object with \( d \) equal to one line width (6.2 MHz in RS-170).
If an object \((d \times d)\) requires an SNR of \(5/(4)^{0.5}\) then the SNR required of one horizontal line through the object is:

\[
\overline{SNR}_{\text{line}} = \frac{5}{\sqrt{4} \sqrt{n_d}}
\]  

(35)

Substituting \(B\) for \(n_d\) using Equation 34, we have:

\[
\overline{SNR}_{\text{line}}(B) = \frac{5}{\sqrt{4} \sqrt{B_0}}
\]  

(36)

If we now assume that we are dealing with x-ray quantum noise that is white, then the SNR spectral noise density and \(\overline{SNR}_{\text{line}}(B)\) are related by:

\[
\overline{SNR}_{\text{line}}(B) = \frac{SNR(f)}{\sqrt{B}}
\]  

(37)

Equating Equation 37 and 36, then:

\[
SNR_{\text{ROSE}}(f) = \frac{5B}{\sqrt{4} \sqrt{B_0}}
\]  

(38)

\(SNR_{\text{ROSE}}(f)\) is therefore the spectral noise density required by a white source of x-rays to produce a total SNR of \(5/(4)^{0.5}\) in one frame for the smallest square object that can be passed in the bandwidth \(0 \rightarrow f=B\). Equation 38 is plotted in Figure 11 and Figure 12 as the Rose threshold for detectability.

The x-ray vidicon and XRII/TV \(SNR(f)\) curves of Figure 11 are similar with the XRII/TV \(SNR(f)\) slightly higher. Both systems maintain a relatively flat \(SNR(f)\) up to the point of equal horizontal and vertical resolution and roll-off above this. A roll-off in \(SNR(f)\) indicates a deviation from x-ray quantum noise limited operation. The roll-off of both systems is similar since the XRII/TV MTF in this mode is dominated by its 1" vidicon which has approximately the same relative MTF as the x-ray vidicon. The Rose line shows that above the point of equal horizontal and vertical resolution, visibility is not possible in the low exposure rate parts of the image.

\(SNR(f)\) for the Cardiac Cine case is shown in Figure 12 for both the large area x-ray vidicon and XRII/TV. The Rose line for detectability (dotted) is also shown \((B_0=22.3\text{ MHz})\). Similar to the Standard Fluoroscopy case, both systems are approximately equal up to the point of equal horizontal and vertical
Above this point, however, the XRII/TV system MTF drops more rapidly than does the x-ray vidicon. The x-ray vidicon $SNR(f)$ in this region is therefore, superior to the XRII/TV system. Again, the Rose line shows that above the point of equal horizontal and vertical resolution, visibility is not possible in the low exposure rate parts of the image.

While the MTF curves of Figure 6 would imply that the x-ray vidicon is superior to the XRII/TV system, the curves of SNR (Figures 11 and 12), show both systems to be roughly equal up to the point of equal horizontal and vertical resolution. This can be explained by the fact that for both systems, the MTF causes both the signal as well as the x-ray quantum noise to fall equally with increasing spatial frequency. The value of $SNR(f)$ is, therefore, a constant as long as x-ray quantum noise reduced by the MTF exceeds electronic noise. It would, therefore, seem that the superior MTF of the x-ray vidicon offers no advantage since the MTF of the XRII/TV could be boosted to match the x-ray vidicon while maintaining a quantum noise limited system. Whether this can be done in practice, depends on the structural noise of the XRII.

Structural noise or fixed pattern noise in the XRII is mainly due to granularity in the input and output phosphors and has been measured to be about 3% of the average signal in a given region. This level is below the minimum detectable contrast for the eye (~4%) so that structural noise is not noticed in a standard XRII/TV image. Boosting the XRII/TV MTF would make structural noise noticeable and objectionable unless it could be removed in some way. When analysing an XRII/TV system it is common to ignore structural noise as we have done. This is justified by the fact that when characterizing an XRII/TV system, structural noise can be removed by a flat field correction or in the case of noise measurements, by the subtraction of two consecutive frames. For a flat field correction to work, the images to be corrected must not shift relative to the flat field image. While this condition can be met in the laboratory, it cannot be met in clinical practice since the XRII moves relative to the earth's magnetic field causing an image shift, and also due to drift in the light sensitive vidicon's raster scan. In practice, the degree of MTF boosting done in an XRII/TV system is minimal. So, while both the XRII/TV and x-ray vidicon systems are quantum noise limited when only x-ray noise and electronic noises are considered, the XRII/TV has an extra structural noise that cannot be removed in clinical practice. The superior MTF of the x-ray vidicon, therefore, gives it an advantage over the XRII/TV system.

D) VEILING GLARE

In an XRII/TV system many processes contribute to a loss of contrast and MTF. These can be divided into short range and long range effects. Short range effects such as light scatter in the input and output
phosphors give the measured line spread function its characteristic shape and are the dominant factor in determining MTF above ~0.1 lp/mm. Long range processes such as x-ray scatter inside the intensifier and halation in the output window\textsuperscript{26} produce a relatively large constant background offset to the resultant image. This relatively constant background is called veiling glare.

Veiling glare is measured using a quantity called the contrast ratio or contrast factor. Contrast ratio (CR) is determined by measuring the signal produced at the centre of an irradiated XRII and comparing it to the signal produced when the central 10\% of the XRII input area is blocked with lead\textsuperscript{1}. (Typically at 50 kVp).

\[
CR = \frac{S}{S_o}
\]

Where: 
\( S \) = signal at centre of unblocked XRII
\( S_o \) = signal with center 10\% area blocked

Typical values of contrast ratio for a modern 9\" XRII\textsuperscript{5,14,42} are 20:1 to 30:1. Smaller XRII's tend to have larger contrast ratios. Another quantity called the small detail contrast ratio is often used to provide veiling glare information. The small detail contrast ratio is measured in the same manner as the normal contrast ratio except that a 10 mm lead disk is used. Typical values are \( \approx 14:1 \). Early XRII's had poor small detail contrast ratios (7:1) which have been improved by the use of fibre optic and thick glass output windows to reduce halation\textsuperscript{5}.

The effect of veiling glare on the XRII MTF is to cause an initial drop in the MTF between 0 and 0.1 lp/mm called the low frequency drop\textsuperscript{41,26}. Typical low frequency drop (LFD) for an XRII is between 5 and 20\% (MTF at 0.1 lp/mm, 80-95\%). The low frequency drop can be found by measuring the value \((1/CR)\) for different radii lead blockers. The value of \(LFD\) is then equal to the value of \((1/CR)\) when extrapolated to zero disk radius\textsuperscript{44,45}.

The x-ray vidicon should exhibit greatly reduced veiling glare when compared to an XRII. Some of the major sources of veiling glare in the XRII such as halation in the output window, light scatter in the input phosphor, light scatter in the output phosphor and retrograde light flow do not occur in the x-ray vidicon. X-ray scatter mechanisms do occur in the x-ray vidicon such as x-ray scatter from the input window, x-ray scatter in the photoconductor, x-ray scatter from the tube walls back toward the photoconductor and k-fluorescence reabsorption in the photoconductor. The fact that the x-ray vidicon photoconductor is flat
as opposed to spherical (as it is in the XRII) will help to reduce x-ray scatter and k fluorescence from the photoconductor from being absorbed by the photoconductor. The low k-fluorescence energy of a-Se (11.2 keV) also reduces its probability of escape from the photoconductor and reduces its effect if it does.

An important question is, will an increase in contrast ratio provided by an x-ray vidicon be of value when compared to a typical XRII contrast ratio of 20:1.

The reduction in contrast caused by veiling glare can be calculated using:

$$C_f = C_s \left(1 - \frac{1}{CR}\right)$$  \hspace{1cm} (40)

Where:  
- $C_f$ = XRII Image Contrast  
- $C_s$ = Subject Contrast  
- $CR$ = Contrast Ratio

For an object with $C_s=10\%$ and $CR=20$, we get $C_f=9.5\%$. This does not represent a significant loss in contrast and the higher contrast ratio of an x-ray vidicon offers little advantage under these conditions.

One source of veiling glare not caused by the XRII/TV system is x-ray scatter in the patient. The level of x-ray scatter varies widely depending on the thickness of the body part imaged and the field of view. The ratio of scattered x-rays to primary x-rays used for the image can be 2:1 to 6:1 in fluoroscopic\footnote{Fluoroscopic procedures} procedures. Fortunately anti-scatter grids can be used to reduce scatter to primary ratio at the detector to about 2:1. The same anti-scatter grids could be used with the x-ray vidicon to provide the same advantage.

E) DYNAMIC RANGE

There is no commonly accepted definition for the term dynamic range (DR). Some of the popular definitions are given below along with their value for the x-ray vidicon.

1) $DR$

Some define dynamic range as the ratio of the maximum signal to the noise level in the black (no illumination). This makes (DR) equal to the electronic SNR at maximum signal and maximum bandwidth\footnote{Electronic bandwidth}. 
For an XRII/TV the maximum signal is $-1 \, \mu \text{A}$ (limited by beam current) and the electronic noise in the black is $-1 \, \text{nA rms (5 MHz)}$. $DR_1$ for an XRII/TV is therefore $\approx 1000$. For an x-ray vidicon, electronic noise in the black is higher ($\approx 3 \, \text{nA rms in 5 MHz}$, for a 9" vidicon) but the maximum beam current can also be made higher. The maximum beam current and thus $DR_1$ will depend on resolution requirements and the type of cathode used (see Chapter 3). The value of $DR_1$ for a large area vidicon should also be about 1000. $DR_1$ is a commonly used parameter for evaluating light sensitive vidicons where electronic noise is usually dominant. An x-ray vidicon is usually x-ray noise dominated and therefore $DR_1$ is of limited value.

2) $DR_2$

Another definition for dynamic range is the ratio of maximum useful signal to minimum useful signal that can be found in the same image$^{13}$ and is given by:

$$DR_2 = \frac{i_{x(\text{max})}}{i_{x(\text{min})}}$$

$DR_2$ is usually evaluated in the presence of a patient and is dominated by x-ray scatter. For the same patient conditions and same grid the value of $DR_2$ for the XRII/TV and x-ray vidicon will be the same.

If $DR_2$ is evaluated in a scatter free environment, it becomes limited by the contrast ratio of the imaging device. For an XRII/TV $CR_{20}$, and therefore the scatter free$^{12} \, DR_2 \approx 20$. An x-ray vidicon with its higher CR will have a higher scatter free $DR_2$.

3) $DR_3$

A useful DR definition for evaluating the x-ray imaging detector itself is the ratio of maximum to minimum signal for which the system is quantum noise limited.
\[
DR_j = \frac{i_{x(max)}}{i_{s(QNL)}}
\]  

(43)

Where: \(i_{s(QNL)}\) = signal current for which x-ray SNR(f) equals electronic SNR(f) at \(f=f_{max}\)

The value \(i_{s(QNL)}\) can be found by equating \(i_{as}(f)=i_{x}(f)\) at \(f=f_{max}\) (Equations 9, 10 and 15) which gives:

\[
2\pi e_n C_s f_{max} = \sqrt{2e i_{s(QNL)} G} MTF(f_{max})
\]  

(44)

\[
i_{s(QNL)} = \frac{2\pi^2 e_n^2 C_s^2 f_{max}^2}{MTF^2(f_{max}) eG}
\]  

(45)

Where: \(G = e/W\) for the x-ray vidicon and \(g\) for the XRII/TV

Values of \(i_{s(QNL)}\) have been evaluated for both the x-ray vidicon and XRII/TV and are shown in Table 5 for Standard Fluoroscopy and Cardiac Cine modes. The values \(e_n\) and \(C_s\) are taken from Table 3 for an XRII/TV with normal 1" vidicon and an x-ray vidicon with suppressor mesh. For Standard Fluoroscopy mode \(f_{max} = 5\) MHz and for Cardiac Cine mode \(f_{max} = 20\) MHz. \(MTF(f_{max})\) is taken from Figure 6 using \(f_s = 0.85\) lp/mm for Standard Fluoroscopy and \(f_s = 3.4\) lp/mm for Cardiac Cine.

<table>
<thead>
<tr>
<th></th>
<th>X-ray Vidicon</th>
<th>XRII/TV</th>
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</thead>
<tbody>
<tr>
<td>Standard Fluoroscopy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9&quot;, 5 MHz, 525 line</td>
<td>23 nA</td>
<td>5.2 nA</td>
</tr>
<tr>
<td>Cardiac Cine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5&quot;, 20 MHz, 1000 line</td>
<td>373 nA</td>
<td>2080 nA</td>
</tr>
</tbody>
</table>

Table 5. Values of \(i_{s(QNL)}\) for both the x-ray vidicon and XRII/TV in Standard Fluoroscopy and Cardiac Cine modes.

If we assume an upper signal current \(i_{s(max)}\) of 1500 nA for both the XRII/TV and x-ray vidicon then \(DR_j\) values are given in Table 6.
Table 6. \( DR \) for different cases assuming \( i_{(\text{max})} = 1500 \) nA

For Standard Fluoroscopy, the MTF of both systems is fairly good up to \( f_{\text{max}} \) but the electronic noise of the XRII/TV system is lower. This gives the XRII/TV a wider dynamic range under these conditions, (ie. the XRII/TV is quantum noise limited down to a lower exposure rate).

For Cardiac Cine, the MTF of the systems become important. The low MTF of the XRII at \( f_{\text{max}} \) causes the x-ray quantum noise to be considerably reduced \( (MTF(f_{\text{max}}) = 0.1) \) such that the XRII/TV system is not quantum noise limited at \( f_{\text{max}} \) for \( i_i < 1500 \) nA. Although the x-ray vidicon has higher electronic noise than the XRII/TV its superior MTF in Cardiac Cine \( (MTF(f_{\text{max}}) = 0.6) \) allows quantum noise at \( f_{\text{max}} \) to dominate electronic noise for signal currents above 373 nA.

Therefore for high resolution fluoroscopy (Cardiac Cine) the \( DR \) of the x-ray vidicon exceeds the XRII/TV system.

F) **Detective Quantum Efficiency**

Inherent to the x-ray image emerging from a patient is quantum noise and a finite SNR in the image. An ideal imaging system does not add noise and therefore produces a SNR at its output that is equal to the SNR in the x-ray photon image at its input. All real imaging systems add noise however, and a quantity called \( DQE \) (detective quantum efficiency)\(^{47,48,49,5,42,26} \) is a measure of how close to ideal an imaging system is at retaining input image SNR. \( DQE \) is given by:

\[
DQE(f) = \frac{SNR_{\text{out}}^2(f)}{SNR_{\text{in}}^2(f)}
\]

An ideal imaging system has \( DQE(f) = 1 \) for all \( f \) of interest. In most imaging systems however, the \( DQE \) curve is highest at zero spatial frequency and decreases for \( f > 0 \). \( DQE(0) \) is therefore an important
quantity as it defines in a sense a starting point for the rest of the $DQE$ curve.

$DQE(0)$ is a commonly measured quantity of the XRII alone (not including the TV system). $DQE(0)$ of XRII is given by:

$$DQE(0) = \eta DQE_{\text{scint}} \quad (47)$$

The quantity $\eta$ is the quantum efficiency or ratio of x-rays absorbed to x-rays incident, while $DQE_{\text{scint}}$ is called the Swank factor and accounts for the added noise due to fluctuations in the amount of light produced per absorbed x-ray. Many factors contribute to this gain fluctuation$^{5,42,47}$ but the dominant contribution is due to the escape of k-fluorescent x-rays from the CsI phosphor. When monoenergetic x-rays above the k-edge of CsI are used, the XRII produces two sizes of light pulse at its output depending on whether or not a k-fluorescent x-ray has escaped from the phosphor. Pulse height distributions at the output of the XRII's have been determined which show $DQE_{\text{scint}} \sim 90\%$ over a wide variation in CsI thickness and x-ray energies used in fluoroscopy$^5$. $\eta$ for an XRII with 400 $\mu$m CsI is $-68\%$ at 90kVp. $DQE(0)$ is therefore $-61\%$.

A Swank factor for the x-ray vidicon can be defined as the DQE reduction factor due to variations in the number of electrons produced in the $a$-Se per absorbed x-ray. We can estimate $DQE_{\text{scint}}$ for the x-ray vidicon from knowledge about k-fluorescence in $a$-Se. In $a$-Se the k-fluorescence is 11.2 keV and the fluorescent yield$^{30,51}$ is $-60\%$. For $W=50$ eV, and an average x-ray photon energy of 47.5 keV (90 kVp), the number of electrons produced in the $a$-Se is 950 and 700 for full absorption and absorption with k-escape. For our electron pulse height distribution we will assume two equal sized peaks at 950 and 700 electrons. The variance ($\sigma^2$) for two equal peaks spaced 250 electrons apart is $(0.5)(250)^2=31250$ ($\sigma=176.8$). $DQE_{\text{scint}}$ can then be evaluated using$^{26}$:

$$DQE_{\text{scint}} = \frac{G^2}{G^2 + \sigma_G^2} \quad (48)$$

Where: $G \quad =$ gain 
$\sigma_G^2 \quad =$ variance in gain
For G=825 ((950+700)/2) and $\sigma^2=31250$, $DQE_{\text{eval}}=0.96$. This value is sufficiently close to 1 that we can ignore it for our purposes and assume:

$$DQE_{\text{eval}}(0)-\eta$$

(49)

$\eta$ and therefore $DQE_{\text{eval}}(0)$ are about 52% for an x-ray vidicon (500 $\mu$m a-Se) at 90 KVP.

III. CONCLUSIONS

The preceding analysis of the signal and noise in a large area x-ray vidicon was done with parameters for a standard 500 $\mu$m xeroradiographic plate at a standard bias field of $10^7$ V/m. A calculation of the expected signal at the vidicon preamplifier input shows it to be approximately the same as that of an equal size XRII/TV system at the same exposure rate. X-ray quantum, Johnson, electron shot and amplifier noise sources were evaluated and compared. Johnson and electron shot noises were found to be negligible compared to x-ray quantum noise under all conditions. The dominant electronic noise source is amplifier noise which has a spectral density that increases with frequency. Amplifier noise is dependent on target stray capacitance which is higher in the large area vidicon due to its larger target. Target stray capacitance of a 9" x-ray vidicon is about 9 times larger than in the 1" vidicon of an XRII/TV system assuming the same relative resolution. Assuming a properly matched preamplifier to the large area vidicon the amplifier noise will be $(9)^{0.35} = 3$ times larger than an XRII/TV system.

Noise sources were compared at the preamplifier input after passing quantum noise through the appropriate MTF. For the large area x-ray vidicon a theoretical MTF based on a cosine squared beam profile was used while a published MTF was used for the XRII/TV. Noise spectral density curves were calculated for both systems for a low resolution, low exposure rate Standard Fluoroscopy mode and for a high resolution, high exposure rate Cardiac Cine mode. In Standard Fluoroscopy mode the XRII/TV is quantum noise dominant up to the point of equal horizontal and vertical resolution. The higher amplifier noise of the large area vidicon however caused it to be amplifier noise dominant in the dark parts of the image near the point of equal horizontal and vertical resolution. In Cardiac Cine mode the poorer MTF of the XRII/TV caused quantum noise to fall well below amplifier noise at high spatial frequencies (2 - 5 lp/mm). The roll-off of quantum noise in the large area vidicon however is less and quantum noise limited operation is maintained out to higher spatial frequencies than in the XRII/TV system.

SNR spectral density curves were calculated for the same four cases as noise. A Rose criterion line was also added to the graphs below which there is insufficient SNR for visualization. For Standard
Fluoroscopy mode the $SNR(f)$ of both systems is approximately equal. For Cardiac Cine mode the superior MTF of the large area vidicon results in a higher SNR at high spatial frequencies. An important consideration when comparing the x-ray vidicon and XRII/TV systems is structural noise of the XRII. While this noise can be removed under laboratory conditions it cannot be removed in clinical practice. This limits any boosting of the XRII/TV system MTF. The superior MTF of the x-ray vidicon therefore offers a distinct advantage over the XRII/TV system. This advantage is greatest in cardiac cine (high resolution) mode where it promises to improve the visibility of small structures.
REFERENCES


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CHAPTER 3

FEASIBILITY OF A LARGE AREA X-RAY SENSITIVE VIDICON FOR MEDICAL FLUOROSCOPY: RESOLUTION AND LAG FACTORS

I. INTRODUCTION

The x-ray image intensifier and television combination (XRITV) is currently the system of choice for real time x-ray imaging. When XRII zoom modes are employed (ie.: 6" and 4.5" diameter) light scatter within the XRII phosphors becomes the limiting factor in the XRII/TV system MTF. A directly x-ray sensitive large area vidicon using an a-Se photoconductor is capable of higher MTF in zoom mode due to the high intrinsic resolution of the a-Se layer. MTF in this case is determined mainly by the MTF of the electron beam readout. When not in zoom mode the MTF of both systems is largely determined by the number of scan lines used and by the electronic bandwidth of the systems.

In fluoroscopic x-ray imaging the signal obtained in a single frame should contain little or no signal from previous frames. That is it must have low lag. Lag has two major components. The first is photoconductive lag, which depends on the quality of the photoconductor and the field applied to it. The second is beam discharge lag which depends on photoconductor thickness, area and current, as well as on the energy spread of the electrons in the scanning electron beam. In the design of a large area x-ray vidicon one must ensure that both types of lag are kept to an acceptable level.

MTF and lag in a large area x-ray vidicon are determined by a great number of interrelated factors. One must understand the various tradeoffs between these factors in order to achieve a design optimized for medical fluoroscopy.

II. FEASIBILITY

A. RESOLUTION

All modern XRII/TV systems use a CsI input phosphor in the XRII. The CsI phosphor has a columnar structure which helps to guide light to the phosphor surface and improve MTF. Even with this improvement over the earlier powder phosphors, the input phosphor has the worst MTF of all the components in the XRII. The second lowest MTF is due to the electron optics followed by the output phosphor. These MTF components along with the total XRII MTF are shown in Figure 1\(^2\). Note that the MTF of the XRII in Mag 2 mode (4.5" diameter) is only slightly better than the MTF of the XRII in Normal mode (9" diameter). This is a result of the input phosphor being the limiting MTF component in both modes.

The MTF of the 1" light sensitive vidicon of the XRII/TV system relative to the XRII input plane will depend on the XRII zoom mode. The MTF’s of the 1" light sensitive vidicon, XRII and XRII/TV combination are shown in Figure 2 for the 9", 525 line system and in Figure 3 for the 4.5", zoom mode of 9", 1000 line system. These extreme cases illustrate that for large area, low line number XRII/TV systems the 1" vidicon is the limiting factor on the MTF, while the XRII is the limiting factor when zoom mode and high line numbers are employed. In both cases the 1" light sensitive vidicon has a superior MTF to the XRII/TV combination, especially in zoom mode. Therefore, if a fluoroscopic x-ray imaging system could be made with a perfect MTF for the XRII, and was limited only by the MTF of the 1" light sensitive vidicon, it would be significantly better than the composite XRII/TV system.

This "perfect XRII" cannot be made, but, we believe that a large area vidicon can be made whose MTF relative to the x-ray input plane is equal to or greater than the MTF of a 1" light sensitive vidicon relative to the XRII input. To a first approximation this statement can be justified by considering the large area vidicon to be scaled up version of the 1" vidicon, preserving the same number of TV lines in the vertical direction and the same electronic bandwidth in the horizontal direction. It is a property of a space charge free electrostatic system that if all tube dimensions are scaled up equally, and voltages are held constant, then the path of electrons in the system will also scale by the same amount.

The factors which contribute to the MTF of a large area x-ray vidicon will be examined with a view to determining the theoretical limitations and optimum tube design. The approach will be to show how MTF can be calculated from the beam spot profile and then show how the desired spot size can be achieved.
Figure 1. MTF of the modern XRII and its internal components relative to the input plane (From deGroot'). Normal mode refers to a 9" diameter field of view while Mag 2 mode refers to a 4.5" diameter field of view. For comparison the MTF of a typical rare earth screen used in film screen radiography is also shown.
**Figure 2.**

MTF of the modern XR111 along with the 1” vidicon and X-ray Vidicon relative to the input plane for a 9” field of view and 525 lines.

**Figure 3.**

MTF of the modern XR111 along with the 1” vidicon and X-ray Vidicon relative to the input plane for the 4.5” zoom mode of a 9” diameter system and 1000 lines.
Various undesired effects which tend to increase spot size are presented and the dominant effects are separated from those which are negligible.

1) **Charge Image Resolution**

The electrostatic charge image produced at the surface of an $a$-Se plate shows very fine detail. The main reason for this is that charge carriers created in the $a$-Se bulk by x-ray absorption are pulled by the electric field with a force that is nearly perpendicular to the surface. This is in contrast to the phosphor in an XRII in which light photons produced in the phosphor bulk reach the surface by scattering and diffusion.

Factors which contribute to charge image resolution of the sensor are:

1) X-ray tube focal spot
2) Patient motion
3) Non-perpendicular x-ray incidence
4) X-ray scattering within the $a$-Se layer
5) Spatial distribution of carriers created
6) Diffusion of carriers during transport
7) Lateral motion of surface charge

Factors 1 and 2 are the same for an x-ray vidicon as they are for an XRII/TV system and should be minimized appropriately. Factor 3 relates to the fact that the $a$-Se layer has a finite thickness and x-rays with non-perpendicular incidence will be absorbed over a non-negligible lateral extent. If we consider the case of a 9" diameter x-ray vidicon with 500 $\mu$m $a$-Se and a focal spot to $a$-Se distance of 75 cm we find x-ray absorption at the edge of the image occurs over a lateral distance of 76 $\mu$m. This geometrical effect should therefore not be a problem in typical fluoroscopic situations where resolution above 5 lp/mm is considered extremely high.

Factors 4, 5, 6, and 7 are difficult to evaluate theoretically but experimental evidence shows that these effects must be small. Xeroradiographic $a$-Se plates exposed to x-rays and readout using toner have been shown to have 50% modulation at a spatial frequency of 20 lp/mm. Others have optically exposed xeroradiographic plates and shown resolution of 200 lp/mm. Also the surface image can be held for many tens of minutes without loss of resolution indicating that factor 7 must be low. A theoretical evaluation of the limitation of $a$-Se resolution for x-rays is given by Que and Rowlands. The above evidence indicates that the process of charge image creation on the $a$-Se surface will not be a limiting
2) **The Raster Scan**

Almost universally, television images are made up of a number of scan lines arranged horizontally. The electron beam in the vidicon or in a television CRT scans in a fixed pattern called the raster. In North America the most common television standard called RS-170 contains 525 lines per frame (1/30 s) of which 483 are active, i.e. visible. The other lines are part of the vertical retrace and are blanked. The RS-170 standard uses interlaced scanning which means that odd numbered lines are scanned in the first 1/60 s called a field while even lines are scanned in the next 1/60 s. An odd field and an even field therefore completes a frame. Interlacing allows the frame rate to be kept low (just above the threshold for the illusion of continuous motion) while eliminating the perception of flicker.

The RS-170 (525 line) standard is used in many fluoroscopic imaging systems. There is a growing trend however, toward fluoroscopic systems which use a greater number of lines. There is no standard number but many employ ~1000 lines though reports are available on 2000 and 4000 systems. The synchronization signals and timing used in systems with more than 525 lines are usually modelled after the RS-170 standard.

The number of scan lines that should be used is a complicated issue. A major factor in the decision, however, is the exposure used per frame. For standard low dose fluoroscopy 525 lines is usually adequate since resolution is limited by the finite number of quanta being used. Higher dose procedures can effectively utilize more scan lines.

While most real-time fluoroscopic imaging uses interlaced scanning some systems designed for pulsed fluoroscopy, fluorography, or DSA utilize progressive scanning. Progressive scanning involves scanning all the video lines in numerical order to complete one frame. Progressive scanning is required whenever the x-ray exposure is discontinuous. If interlaced scanning is used in such a case the odd and even fields do not combine properly to form a frame. The reason is that the electron beam always overlaps onto the line above and below causing the first field to steal signal from the second field.

Resolution in the vertical direction due to the scanning process is determined by the number of lines per unit distance and by the size of the electron beam spot. If we assume a beam spot diameter approximately
equal to the line spacing then the limiting vertical resolution can be estimated from\(^{10}\):

\[
f_{v(\text{max})} = \frac{Sak}{2d_v}
\]  

(1)

Where: 
- \(f_{v(\text{max})}\) = limiting vertical resolution (lp/mm)
- \(S\) = Nominal number of TV lines (525 for RS-170)
- \(a\) = ratio of active to nominal number of TV lines (-0.92)
- \(d_v\) = vertical distance spanned by active lines (mm)
- \(K\) = Kell factor (-0.7)

The Kell Factor\(^{11,12,9}\) is a quantity which relates the number of scan lines used to form an image to the number of horizontal bars that could be viewed on the system. Subjective viewing experiments have shown that bar patterns up to 70% of the Nyquist frequency \((f_n=Sa/2d_v)\) may be recognized without spurious beat patterns being observed by an average viewer. The fact that adjacent lines partially overlap has been included in the Kell factor\(^{11}\). This overlap is necessary since practical electron beams do not have abrupt profiles. Also, if the effective beam spot is too small, flicker can result from the incomplete discharge of the area between the scan lines\(^{13}\).

The results of applying Equation 1 to determine \(f_{v(\text{max})}\) for a 9" x-ray fluoroscopic system with a 4.5" zoom mode and either 525 and 1023 are given in Table 1.

<table>
<thead>
<tr>
<th>Line Number</th>
<th>9&quot; Diameter</th>
<th>4.5&quot; Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>525 line nominal</td>
<td>0.73 lp/mm</td>
<td>1.5 lp/mm</td>
</tr>
<tr>
<td>1023 line nominal</td>
<td>1.4 lp/mm</td>
<td>2.9 lp/mm</td>
</tr>
</tbody>
</table>

Table 1. Limiting vertical resolution, \(f_{v(\text{max})}\)

In an x-ray vidicon or any raster scanned television system it is desirable that the limiting factor in determining the vertical resolution be the number of lines used. This is not the case in XRII/TV systems when high line numbers and zoom mode is employed. An x-ray vidicon, however, should fulfil this requirement.

While the vertical direction of a TV image is sampled in a discrete manner, the horizontal direction is continuous. Resolution in the horizontal direction due to the scanning process is determined by the size of the electron beam spot and by the electrical bandwidth. It has been found that the current density distribution in an electron beam is closely approximated by a cosine squared function\(^{14}\), i.e.:
\[
J(r) = J_0 \cos^2 \left( \frac{\pi r}{4r'} \right) \quad |r| \leq 2r' \\
= 0 \quad |r| > 2r'
\]

(2)

Where:
- \( J(r) \) = current density
- \( r \) = distance from centre of beam
- \( r' \) = FWHM radius
- \( J_0 \) = constant of proportionality

The MTF for the beam profile of Equation 2 is obtained as the Fourier transform and thus the beam component of horizontal MTF is\(^{14}\):

\[
MTF_{H, \text{beam}}(f_s) = \frac{\sin(4\pi r' f_s)}{4\pi r' f_s(1-(4r' f_s)^2)}
\]

(3)

Where:
- \( f_s \) = spatial frequency

This MTF expression was used in Chapter 2 as a typical vidicon MTF. This is justified by the fact that it accurately predicts the measured MTF of 1" light sensitive vidicons\(^{15}\). Equation 3 has been used to calculate the theoretical MTF of a large area vidicon and is shown in Figure 2 for the 9", 525 line mode (\( r' = 0.237 \text{ mm} \)), and in Figure 3 for the 4.5", 1000 line mode (\( r' = 0.062 \text{ mm} \)). In both cases, the theoretical x-ray vidicon MTF is similar to that of a 1" Saticon\(^{16,17}\) referenced to the same input area. (N.B. The MTF curves do not include the effect of amplifier bandwidth.) Determination of the beam spot size and theoretical limitations of the spot size are discussed later. It should be noted that Equation 3 represents a first order approximation to the actual electron beam MTF. In practice, the beam spot deviates from radial symmetry due to: 1) the overlap of scan lines; 2) the beam being bounded above by a discharged region and below by an undischarged region; and 3) the leading edge of the beam providing more readout current than the trailing edge (self-sharpening).

3) **Electronic Bandwidth and Resolution**

Charge distribution spatial frequencies, in the horizontal direction, are converted to signal current temporal frequencies by the electron beam readout process. The signal is then passed through a number of amplifying stages to form the final video signal. The horizontal MTF of the displayed image is thus dependent on the MTF due to spot size as well as the frequency response of the complete amplifier chain. The amplifier chain is usually designed to have a flat response up to some frequency or bandwidth B and
then roll-off quickly above this. The exact shape of the roll-off, and thus MTF due to the amplifier varies with amplifier design.

Limiting horizontal resolution due to the amplifier bandwidth \( B \) is given by:

\[
f_H = \frac{B t_H}{d_H}
\]

Where:
- \( f_H \) = limiting horizontal frequency (lp/mm)
- \( B \) = bandwidth (Hz)
- \( t_H \) = active horizontal scan time (\( t_H = 52 \mu s \) in RS-170)
- \( d_H \) = horizontal scan width (\( d_H = 4/3d_v \) in RS-170)

Television systems are usually designed such that horizontal and vertical resolutions are equal. An exact match is not critical however, since the human observer is relatively insensitive to a resolution mismatch\(^{12}\).

The amplifier bandwidth should be adjusted to match the desired horizontal resolution. The desired bandwidth for equal horizontal and vertical resolution is found by equating Equations 1 and 4, that is:

\[
B = \frac{SaKd_h}{2d_fH}
\]

For a 525 line RS-170 system (\( S = 525, a = 0.92, K = 0.7, \) \( d_h = 4/3d_v \), and \( t_H = 52 \mu s \)), \( B = 4.3 \) MHz. In fluoroscopic television \( B \) is usually adjusted to be about 5 MHz\(^{18}\). For simplicity we will use 5 MHz as our RS-170 bandwidth and 20 MHz for the 1000 line system bandwidth. By using values of \( B \) larger than these, horizontal resolution may be made larger than vertical resolution. Note that bandwidth varies as the square of the number of lines used since \( t_H \) also varies inversely with the number of lines.

A slightly higher horizontal resolution can be obtained in a vidicon by use of an aperture correction circuit. This circuit preferentially boosts high frequencies in such a way as to compensate the low pass filtering action of the electron beam spot. The technique has the disadvantage of also increasing high frequency noise.

\[4) \quad \text{Focus and Deflection Methods}\]

A number of methods of focusing and deflecting electron beams by the use of electric and magnetic fields are known. These methods will now be described and the best method for use in a large area vidicon will be determined. The principal components of a large area vidicon electron-optical system are shown in Figure 4. The purpose of the electron source is to produce as near as possible a point source of electrons.
Figure 4. Principal components of a large area vidicon electron-optical system.

Beam width is exaggerated

Figure 5. The triode and diode electron source (gun).
The cone of divergent electrons produced by this source is then focused by the lens to form an image of the point source at the target plane. The collimator lens is used to make the deflected electron beam land perpendicular to the target and the suppressor mesh is used to prevent instabilities in the target surface potential caused by secondary electron emission. The collimator lens and suppressor mesh will be described in more detail later.

a) *Triode and Diode Sources*

The electron source most commonly used in electron guns is the triode shown in Figure 5A. The G1 electrode is negative and the G2 electrode positive so the paths of the electrons from the cathode form a crossover that has a cross-section much smaller than the emitting area of the cathode. It is this crossover which is imaged onto the target. In some cases the G2 aperture is made smaller than the crossover and then the G2 aperture is imaged onto the target. In television CRTs, the crossover is generally imaged while in a 1" vidicon it is the G2 aperture\(^{19}\). Beam current is controlled by varying the negative potential on G1. By making G1 low enough with respect to the cathode the beam can be completely cut off.

Another type of electron source is the diode structure shown in Figure 5B. The diode differs from the triode in that the G1 electrode is positive with respect to the cathode and therefore current flows from the cathode to G1. Electrons emerging from the G1 aperture can be used as a point source directly\(^{20}\) or a crossover may be formed as in the triode\(^{21,22,23}\). The advantage of the diode structure is that it produces an electron beam with a lower spread in axial electron energy. This is advantageous in reducing beam discharge lag. Electron energy spread in excess of that normally due to cathode emission (\(E=KT/e\)) can occur in regions of high current density due to space charge effects (mutual repulsion of electrons in the beam causing it to expand). The diode gun has a lower energy spread because it either has no crossover or the electron velocity at the point of crossover is higher\(^{21}\).

Most vidicons and CRTs use an oxide coated cathode. It is formed by coating the end of a nickel cathode cylinder with barium and strontium carbonates in a binder\(^{19,24}\). Upon heating, the carbonates decompose into oxides and elemental barium. The low work function of this surface makes it an efficient thermionic electron emitter at relatively low temperatures (840°C). The current density at the cathode surface, also known as the cathode loading, is typically between 0.25 and 1 A/cm\(^2\). Cathode loading is an important parameter as it relates to maximum beam current and electron spot size. In general the higher the cathode loading the higher the electron beam current can be for a fixed spot size or the smaller the spot size can be for a fixed beam current. High cathode loading, however, results in short cathode life due to positive
ions poisoning the cathode. If the beam current, spot size, and lifetime requirements of a large area vidicon cannot be met with an oxide coated cathode then an alternative dispenser cathode may be needed. The dispenser cathode\textsuperscript{25,24} is capable of higher cathode loading (1-10 A/cm\textsuperscript{2}) and longer life (10-50X) but at added expense and power requirements.

b) \textit{Electrostatic and Magnetic Vidicon Lenses}

The lens used to focus the electron beam can be either electrostatic or magnetic and can have either a short or long extent. By short it is meant that the lens acts on the beam only for a small fraction of the beam's path. Conversely a long lens is one that acts on the beam for most of its travel. Long and short electron-optical systems are shown in Figure 6. Note that in a long electron-optical system, focus and deflection must occur simultaneously.

Three types of electron beam focusing lenses are shown in Figure 7. Although many types of electrostatic lens are known, the einzel lens is by far the most common electrostatic main lens type used in vidicons. The einzel lens\textsuperscript{19}, shown in Figure 7A, consists of three axially symmetric cylinders (G3, G4, and G5). The G3 and G5 are held at the same potential ($V_3=V_5$) and focusing is accomplished by adjusting the potential of G4 ($V_4$). Two focus conditions exist, one for $V_4<V_3$ and one for $V_4>V_3$. The lower $V_4$ case is usually used for convenience. The einzel lens may be used in either a long or short configuration.

Magnetic focus lenses use DC currents in a wire coil to produce the magnetic focusing field. Although permanent magnets have been used for focusing they are not common\textsuperscript{26}. The long magnetic focus lens shown in Figure 7C is simply a solenoidal coil producing a nearly uniform axial field within. If the solenoid is viewed end-on, any electron with a radial velocity away from the central axis will travel in a circle, bringing it back to the central axis. The focus condition occurs when the electrons complete one or more integral loops in the time it takes for electrons to travel from the G2 aperture to the target. The short magnetic lens shown in Figure 7B differs from the long version in that it uses a soft iron core to concentrate the magnetic field across a short gap. In general, magnetic lenses are bulkier and require more power than electrostatic but have the advantage that they can be placed outside the vacuum.

c) \textit{Electrostatic and Magnetic Deflection}

Similar to electron beam lenses, electron deflection may be accomplished using electrostatic or magnetic fields in both a short or long fashion. Three common methods of beam deflection are shown in Figure 8.
Figure 6. Long and short electron-optical systems.

Figure 7. Electron beam focussing lenses.
Short electrostatic deflection is accomplished using deflection plates as shown in Figure 8A. The electron beam is first deflected in one direction followed by deflection in a perpendicular direction. Simultaneous horizontal and vertical deflection using plates is not done since the presence of the horizontal plates would greatly distort the vertical deflection field and vice versa.

A long electrostatic deflection implies that horizontal and vertical deflection must occur simultaneously. A method other than plate deflection must therefore be used. Two methods which achieve simultaneous horizontal and vertical deflection are the multipole yoke and the pattern yoke. Yoke here meaning deflection system with a single centre of deflection. Multipole yokes use 8 (octopole) or more plates arranged radially around the central axis. By applying appropriate potentials to the plates the required deflection field can be approximated. A disadvantage of this method is the large number of voltage wave forms which must be derived and brought into the tube. The most common electrostatic yoke used in vidicons is the pattern yoke shown in Figure 8B. The yoke consists of two horizontal and two vertical electrodes arranged in a zig zag pattern along the tube length. The average field that the electron sees as it passes down the tube is such that horizontal and vertical deflecting are independent and deflection distance is proportional to the applied deflection potential.

Magnetic deflection is accomplished by placing a pair of coils on opposite sides of the tube to produce a magnetic field perpendicular to the electron motion. (see Figure 8C) Another pair of coils can be placed at 90° with respect to the first for simultaneous horizontal and vertical deflection. Long and short magnetic yokes can be made. Deflection uniformity can be improved by adjusting the shape and density of the windings in the yoke.

**d) The Field Mesh and Collimator Lenses**

In a vidicon electrons in the beam are decelerated to near zero velocity as they reach the target. It is desirable to decelerate the electrons in as short a distance as possible to minimize space charge effects (mutual repulsion of electrons in beam causing it to expand) and beam bending. This is accomplished by placing a field mesh parallel to the target. In a 1" vidicon the field mesh is about 3 mm from the target with a pitch of ~1000 holes per inch and a transparency of ~50%. The mesh is typically made of Ni or Cu. Although a field mesh is not strictly required a vidicon without one would have very poor characteristics. Resolution of a vidicon improves as the potential of the field mesh is increased.
A) Parallel Plate Electrostatic Deflection

B) Deflectron Electrostatic Deflection Yoke

C) Perpendicular Coil Magnetic Deflection

Figure 8. Electron beam deflection methods.

Figure 9. Magnification of the crossover by a thin lens.
The field mesh (Figure 4) can be placed at the same potential as the wall (or drift) electrode or it can be given a higher potential than the wall electrode. These are referred to as integral mesh and separate mesh respectively. In a separate mesh vidicon a lens is formed between the wall and field mesh electrodes. This collimator lens causes a deflected beam arriving at an angle to the lens to be bent perpendicular to the target. This is needed to prevent secondary electron emission problems (see Chapter 4), to prevent persistent rippling (waterfall effect) as described at the end of this chapter, and for maintaining a uniform potential across the target surface. In a long magnetic focus vidicon, beam landing correction can be accomplished by the fringing fields of the focus coil with adjustment depending on coil placement. In short magnetic and electrostatic focus systems however, a collimator lens is necessary.

e) The Suppressor Mesh

In vidicons which use a high target potential such as an x-ray sensitive vidicon a suppressor mesh is needed to ensure target stability. (See Chapter 4) The suppressor mesh is placed between the field mesh and the target surface and is held at a potential of about 100V (exact value depends on the properties of the coating applied to the a-Se surface). If the suppressor mesh is located at a distance where the 100V equipotential would normally be found then the electron paths are relatively unaffected by its presence except that the suppressor mesh will absorb about 50% of the beam as does the field mesh. The suppressor mesh pitch requirement is higher since it is closer to the target or point of focus. If it is too coarse it will be seen in the image.

f) Combined Focus and Deflection

Although any combination of focus and deflection method could be used we find almost without exception long focus lenses are combined with long deflection and short focus lenses are used with short deflection. In a long system, focus and deflection occur simultaneously while in a short system the beam is first focused and then deflected. While deflection before focusing is in theory possible, it is rarely done due to severe problems associated with lens aberations.

There are four possible combinations of long focus (electrostatic and magnetic) and long deflection (electrostatic and magnetic). All 1" light sensitive vidicons are one of these four types. In all these configurations, the G2 aperture is imaged onto the target with near unity magnification producing the small spot size required in 1" tube. The most common configuration is the magnetic focus and magnetic
deflection type. It has the advantage of the simplest possible internal tube structure which makes it inexpensive, but has the disadvantage of the heavy and bulky focus and deflection coils required. The magnetic focus electrostatic deflection system is also popular. This system has been reported to approach, and in some cases, exceed the performance of the all magnetic system\textsuperscript{16,19,23}. The electrostatic focus-magnetic deflection\textsuperscript{19,32,35,36}, and all-electrostatic systems have poorer performance. Research continues to improve the all-electrostatic system\textsuperscript{40,41} which has the advantage of having by far the smallest mass.

There are also four possible configurations of short focus and deflection. These methods are popular in television CRT's and oscilloscope tubes. In these four configurations the crossover is imaged onto the target or screen with a magnification greater than unity (typically 5-20). After deflection the beam drifts in a field free region to increase the scan distance at the target. The two magnetically-deflected systems are used in television CRT's because of the low deflection distortion of a magnetic yoke. Magnetic yokes have an associated inductance which makes fast deflection difficult and are better suited to relatively low deflection speed at a fixed scan frequency such as found in a television CRT or vidicon. Electrostatic deflection is used when deflection speed is more important than deflection distortion such as in an oscilloscope. In general a short magnetic focus has less aberrations than a short electrostatic focus but for most purposes the electrostatic focus is sufficiently sharp.

The question which remains now is which of the eight systems is best suited for a large area x-ray sensitive vidicon. The answer to this question depends on tube length, bulk and resolution requirements. Long focus and deflection systems image the electron source onto the target with approximately unity magnification and therefore, can achieve a very small beam spot at the target. Limitations on how small the electron source can be made (~25 \( \mu \)m) make this the only choice for a 1" vidicon. A disadvantage is that if magnetic focus or deflection is employed then the coil used will significantly add to the tube diameter and weight.

If a short focus and deflection system is used, the lens is usually placed closer to the electron source and therefore, as in light optics, the magnification is greater than 1. This allows the lens to be smaller while maintaining the same beam current. (Beam current is related to the solid angle of the electrons from the source which are captured by the lens.) The smaller lens means that the electron source can be housed in a smaller diameter neck. The size of the lens, deflection and overall tube are reduced.

Standard fluoroscopy and cardiac cine characteristically have 525 or 1000 lines, and a zoom diameter no smaller than 4.5". The smallest beam diameter required at the target is therefore, ~125 \( \mu \)m (1000 lines,
Our choices are therefore, to use a long (magnification=1) electron-optical system with 125 μm electron source or else, a short electron-optical system with a standard electron source (~ 25 μm) and a magnification of 5. Since both long and short systems can provide the necessary resolution, the choice will be made on the basis of tube size. The preferred system is therefore, a short one which minimizes tube bulk. The preferred deflection method for a short system is magnetic since it has lower deflection defocusing, which allows a larger deflection angle and the tube to be made shorter. The preferred focus is magnetic due to its smaller spherical abberation, although electrostatic focus is usually adequate. The design of the large area vidicon is therefore, similar to a CRT, i.e. an electrostatic or magnetic lens in or on the neck of the tube and magnetic deflection where the neck meets the body. This design has been used in other larger area vidicons. The 5" x-ray vidicon reported by Suzuki et al42 uses a short electrostatic focus and magnetic deflection while the 4" x-ray vidicon reported by Smith13 uses a short magnetic focus with magnetic deflection.

5) Electron Beam Resolution

In the focusing system of a vidicon, the primary objective is to image the crossover or G2 aperture of the electron source through a lens system onto the target. A number of factors are acting however to limit or distort the final beam spot. These factors include space charge, thermal emission energy spread, lens abberations, deflection defocusing, and image potential effects. The ideal source spot image and factors which limit its realization will now be discussed.

a) Source Spot Magnification

The linear magnification $M$ is the ratio of image spot diameter ($d_{ts}$) at the target to the source spot diameter ($d_{ss}$) at the triode or diode gun ($d_{ss}=2r'$ from Equations 2 and 3). The source diameter can be either the crossover diameter or the G2 aperture diameter.

$$M = \frac{d_{ts}}{d_{ss}}$$

The value of $M$ for a particular system depends on the lens used and its position between the object and image. The short einzel lens and the short magnetic lens that we will be considering will be represented by thin lens approximations. This approximation considers the lens to have a single principal plane and two focal points located equidistant on each side of the plane. For an einzel lens with G3 and G5 the
same size and shape (see Figure 7A) the principal plane is located at the physical centre of the lens or in the centre of G4. For a short magnetic lens the principal plane is located at the midpoint of the magnetic gap. The focal length of the lenses depends on the voltages (electrostatic lens) and currents (magnetic lens) used.

The electron optical arrangement is illustrated in Figure 9. The condition for the focus is given by the well known lens makers formula for light optics.

\[
\frac{1}{f} = \frac{1}{a} + \frac{1}{b}
\]

(7)

Where:  
\( f \) = focal length of lens  
\( a \) = lens to source spot distance  
\( b \) = lens to image spot distance

And the linear magnification is given by:

\[
M = \frac{b}{a} = \frac{d_{IS}}{d_{SS}}
\]

(8)

The value of \( b \) is determined by deflection considerations and therefore the value \( a \) may be adjusted to give the desired \( M \). The focus condition is set during operation by the electrical adjustment of \( f \).

The focal length of an einzel lens depends on the lens geometry and on the relative voltages impressed upon it. Figure 10 shows the focal length versus voltage ratio for a typical einzel lens\textsuperscript{44,45,46}.

The focal length of a short magnetic lens can be calculated analytically using\textsuperscript{30}:

\[
f = \frac{256mRV}{3\pi\mu_o e N^2 I^2}
\]

(9)

Where:  
\( m \) = electron mass \((9.1\times10^{-31} \text{ kg})\)  
\( R \) = inside radius of lens  
\( \mu_o \) = permeability of free space \((1.257\times10^{-6} \text{ H/m})\)  
\( e \) = electron charge \((1.6\times10^{-19}\text{C})\)  
\( N \) = number of turns of coil  
\( I \) = current in coil  
\( V \) = energy of electron in coil
Figure 10. Focal length of an einzel lens. (from Moore et al\textsuperscript{45})
Typical values for a large area vidicon might be $f=5 \text{ cm}$, $R=2.25 \text{ cm}$, $V=700 \text{ V}$, and $N=850$ turns which gives a focus current of $0.2 \text{ A}$.

**b) Beam Defocusing Due to Image Potential**

In our calculation of the beam spot diameter due to magnification of the source spot, it has been so far assumed that the spot is formed in a region of uniform potential (i.e. the potential of the drift region after the lens). In a vidicon, however, the beam at the end of its travel is decelerated as quickly as possible at the target to near zero velocity. The path of electrons in the deceleration region is shown in Figure 11. Electrons which pass through the mesh at some angle other than perpendicular have a parabolic path in the deceleration region. Also depending on the target surface potential only some of the electrons may reach the target surface. The diameter of the spot formed by electrons which reach the target surface is the size defining the resolution.

Lubszynski et al have divided the possible electron paths in the deceleration region into three regimes depending on the target surface potential. At low target potentials only the electrons with near perpendicular incidence may reach the target as shown in Figure 11A. Outer electrons have a greater angle of incidence and therefore reduced axial velocity which is insufficient to reach the target. This regime has been named core acceptance and has a spot size given by:

$$d_s = 2\frac{V_s d}{V_m} \quad V_s < V_m \sin^2 \theta_p$$

Where:
- $d_s =$ diameter of spot
- $V_s =$ target surface potential
- $V_m =$ mesh potential
- $d =$ mesh to target distance
- $\theta_p =$ angle of incidence of peripheral electrons

If the target surface potential is increased, more of the beam will reach the target. The value of $V_s$ for full beam current is given by:

$$V_s > V_s' = V_m \sin^2 \theta_p$$

Where:
- $V_s' =$ target surface potential for threshold of full beam current
A) Core Acceptance
\[ V_s < V_m \sin^2 \theta_p \]
\[ d_s = \frac{2V_s}{V_m} d \]
\[ l = \frac{I_o V_s}{V_m \sin^2 \theta_p} \]

B) Mixed Acceptance
\[ V_m \sin^2 \theta_p < V_s < 2V_m \sin^2 \theta_p \]
\[ d_s = \frac{2V_s}{V_m} d \]
\[ l = I_o \]

C) Simple Acceptance
\[ V_s > 2V_m \sin^2 \theta_p \]
\[ d_s = 4d \sin \theta_p \sqrt{\frac{V_s}{V_m} - \sin^2 \theta_p} \]
\[ l = I_o \]

Figure 11. Electron paths in the deceleration region.
For values of $V_s$ just above this critical value $V'_s$ the electron paths cross before striking the target. This regime is called mixed acceptance as shown in Figure 11B. The spot size for mixed acceptance is also given by Equation 10.

If $V_s$ is increased above a value of $2V'_s$ the electrons paths no longer cross and the regime is called simple acceptance as shown in Figure 11C. The spot size for simple acceptance is given by:

$$d_s = 4d \sin \theta_p \sqrt{\frac{V'_s}{V_m} \sin^2 \theta_p} \quad V_s > 2V'_s$$

(12)

We will now evaluate beam defocusing effects for a large area vidicon. In chapter 2 we showed that a 9" diameter vidicon with 500 $\mu$m a-Se would provide a signal of 62 nA in standard fluoroscopy (30 $\mu$R/s). The minimum and maximum expected signals were 6.2 nA and 620 nA respectively. These are instantaneous signal currents and correspond to average signal currents of 2.7, 27, and 270 nA respectively. The instantaneous and average signals are related by the ratio of active to retrace scan time $K$ (1.33) and the ratio of rectangular scan area to circular x-ray area $\varphi$ (1.7). The layer capacitance of the 9" diameter 500 $\mu$m a-Se layer ($\varepsilon_r=6$) is 4.3 nF. The signal voltages on the selenium surface are given by $V_s=(I_{avg} \Delta t)/C$. For a 1/30 sec frame time the values of $V_s$ are therefore 0.02, 0.2, and 2 volts respectively.

We will assume our large area vidicon to have $V_m=1000$V, $d=30$mm, and $\theta_p=0.15^\circ$. The value of $\theta_p$ is dependent on deflection defocusing considerations to be discussed later. Using Equation 11, $V'_s=6.8$ mV which means that over the range of signal expected ($V_s=0.02$ to 2 V) the beam will be in the simple acceptance regime. Using Equation 12, the spot size for the worst case of $V_s=2$V is $d_s=14$ $\mu$m. This spot size can be thought of as the blurring of each point in the magnified source spot image. The minimum image spot diameter we will need is about 125 $\mu$m (1000 lines in 4.5 diameter) therefore a blurring of -14 $\mu$m at the highest signal is quite acceptable.

In a 1" vidicon the beam semiangle $\theta_p$ is about 1 or 2 degrees which means that all three regimes must be considered. The need to consider only simple acceptance in the large area vidicon is a result of the small beam semiangle chosen ($\theta_p=0.15^\circ$). If the vidicon is designed to have a larger $\theta_p$ than this in order to increase beam current for example then beam deceleration blurring will need to be reevaluated.
c) **Thermal (Langmuir) Limit**

Electrons emitted from the cathode of an electron gun have a velocity distribution both axially as well as radially which is Maxwellian and dependent on the cathode temperature. If electrons were released from the cathode with zero initial energy they could all easily be guided by electric and magnetic fields to form the beam spot. However, the non-zero radial velocity of the emitted electrons limits the fraction of emitted electrons which can be guided into a spot of a given size. Electrons which have large radial velocities are absorbed by the beam stop aperture in the electron gun, which limits the beam diameter and beam semi-angle $\theta_p$. Langmuir has derived a fundamental theorem which gives the maximum current density that can be produced in a beam spot for an arbitrary lens system given some parameters external to the lens system. The Langmuir formula states:

$$\rho_s = \rho_c \left( \frac{V_c}{kT} \right) \sin^2 \theta_p$$

(13)

Where:

- $\rho_s$ = current density of beam spot
- $\rho_c$ = current density of cathode
- $V$ = potential of beam spot region
- $T$ = cathode temperature (absolute)
- $\theta_p$ = beam semi-angle
- $k$ = Boltzmann constant

This formula is actually a limited version of the full Langmuir formula and is valid when the beam current is a small fraction of the cathode current which is always the case in vidicons. Other conditions that are required for the Langmuir formula to be valid are that the cathode current be uniform across its surface, that the lens be aberration free and that the beam spot is measured in a region of uniform potential free of magnetic fields. The geometry associated with this formula is shown in Figure 12.

In practice the Langmuir limit is never reached and a Langmuir nearness of approach$^{24}$ factor of $\eta_L=0.5$ is used. Also a vidicon contains a mesh (or 2 meshes) which each have a transparency $\tau_m$ of about 50%. Incorporating the factors $\eta_L$ and $\tau_m$ along with $I_s=(d_{IS}^2\rho_s)/4$ the Langmuir equation becomes:

$$I_s = \frac{\pi}{4} d_{IS}^2 \eta_L \tau_m \tau_{field} \rho_c \left( \frac{V_c}{kT} \right) \sin^2 \theta_p$$

(14)

Where:

- $I_s$ = current at the beam spot
- $d_{IS}$ = diameter of the beam spot
Figure 12. Geometry used with Langmuir formula.

Figure 13. Geometry used to calculate electron deviation due to space charge.
Using typical values for a 1" vidicon ($d_{is}=30 \mu m$, $n_l=0.5$, $\tau_m=0.5$, $\rho_c=0.25$ A/cm$^2$, $V=1000V$, $k=1.38 \times 10^{-23}$ J/K, $T=1100K$, and $\theta_p=1.5^\circ$) we find $I_r=1.6 \mu A$. This value is in rough agreement with actual 1" vidicons and is sufficient to handle the signals found in standard and cardiac cine XRII/TV fluoroscopy.

For a large area vidicon all factors remain roughly the same except for $d_{is}$ and $\theta_p$. The value of $d_{is}$ is larger since the same number of scan lines are used over a larger area. The value of $\theta_p$ is smaller since the distance from the lens to the target is larger, and the diameter of the beam as it passes through the lens is approximately the same.

For a 9" vidicon it is assumed, all other factors being equal, that $d_{is}$ is 9x larger and $\theta_p$ is 9x smaller and therefore $I_r=1.6 \mu A$. If a suppressor mesh is used, this value will be reduced by -50%. As with the XRII/TV system this level of current is sufficient to handle the range of signals to be expected from the large area vidicon in standard and cardiac cine fluoroscopy.

If larger signal currents are required, say for DSA, then 2 methods of increasing $I_r$ are possible. The first is to increase $\rho_c$ by using a dispenser cathode in place of an oxide cathode. While the dispenser cathode is more costly and requires higher heater power it can provide a current density and thus beam current which is about 12x larger ($\rho_c=3$ A/cm$^2$) than an oxide cathode.

The second method of increasing beam current is to increase $\theta_p$. One must then deal with lens aberrations and deflection defocusing. Lens aberration may be reduced by simply making the lens larger or by replacing an electrostatic lens with a magnetic lens. Deflection defocusing may be reduced by making the tube longer which reduces the deflection angle. Deflection defocusing can also be reduced to some degree by dynamic focusing that adjusts the focus as a function of beam position. A factor of 2x increase in $\theta_p$ should be possible with the above modifications. If we combine the gain in $\rho_c$ with the gain in $\theta_p$ a gain of ~50X (~3/0.25)x(2)$^2$ is possible. Higher currents could be utilized by DSA and fluorography which have exposures per frame that are 10-25 and >25 times higher than cardiac cine respectively. Sufficient current is thus available for DSA but fluorography may require slow scan readout (reduces signal current) or a reduced $\alpha$-Se potential (reduces sensitivity) or both. Reducing $\alpha$-Se potential has the same effect as reducing the aperture in an XRII/TV system.

Overall sufficient beam current is available for standard and cardiac cine fluoroscopy using a "conventional" design but higher currents for DSA are possible using relatively simple modifications if required.
d) *Space Charge Limitations*

The mutual repulsion of electrons in a narrowly focused beam causes a spreading or defocusing of the beam. A number of investigators\textsuperscript{49,50,51,52} have calculated the effects of space charge on a beam focused in a region of uniform potential. Using their results it can be easily shown that space charge is not a problem as the electrons travel from the lens to the field mesh in a vidicon.

As the electrons travel from the field mesh to the target, however, they are being slowed down as they converge on the target. Since this is the region where the electrons move with their lowest velocity and are most tightly focused the deceleration region is the most critical region with respect to space charge.

No analysis of space charge effects in a decelerating field has been found in the literature. Moss\textsuperscript{53} gives an analysis of space charge effects in an accelerating electric field but adaptation of the method to a decelerating field presents mathematical problems.

The trajectory of the electrons is determined by a second order differential equation which could be solved numerically. A simpler method of estimating space charge effects, however, is to assume the electron follows its normal non-space charge trajectory, determine the space charge force that would exist at each position in this trajectory and then calculate the deviation that this force would have on the electron. This method will overestimate the space charge deviation since the repulsive force is calculated for a beam envelope that is narrower than the true envelope.

The outermost electron in a beam of electrons experiences an outward space charge force given by\textsuperscript{54}:

\[
F_s = \frac{le}{2\pi e_0 r_n v_z} = \frac{le}{2\pi e_0 (r_o - v_z t)(v_{zo} - a_z t)}
\]  

(15)

Where:

- $F_s$ = outward space charge force
- $I$ = beam current
- $r$ = radius of beam
- $v_z$ = axial velocity of electrons
- $r_o$ = radius of beam at mesh
- $v_r$ = inward radial velocity of electrons (constant)
- $v_{zo}$ = axial electron velocity at mesh
- $a_z$ = deceleration due to electric field
- $e$ = electron charge
The geometry for this calculation is illustrated in Figure 13. Both the beam radius and velocity decrease as the beam approaches the target. \( r, v_z \) and thus \( F_z \) can be expressed as a function of time. The deviation estimate for the outermost electrons is given by:

\[
\Delta r = \frac{1}{m} \int_0^{t'} \int_0^t F_z \, dt
\]

Where:
- \( \Delta r \) = estimate of electron deviation
- \( t' \) = transit time from mesh to target

If we combine Equations 15 and 16 and integrate, we find:

\[
\Delta r = \frac{I_e}{2\pi \epsilon m (a_z r_o - v_z v_o)} \int_0^{t'} \ln \left( \frac{v_z t}{v_o} \right) \, dt
\]

Integrating once more we find:

\[
\Delta r = \frac{I_e}{2\pi \epsilon m (a_z r_o - v_z v_o)} \left[ \left( t' - r_o \right) \ln \left( \frac{v_z t}{v_o} \right) - \left( r' - \frac{v_z}{v_o} \right) \ln \left( 1 - \frac{a_z t}{v_o} \right) \right]
\]

In the analysis it is assumed that the surface potential of the target \( V_t \rightarrow 0 \). Also we will assume that a suppressor mesh if present is in such a position and potential that it does not disturb the original potential distribution. Note that when properly focused the trajectory of electrons associated with a given point in the beam spot would converge at a distance \( d \) behind the target\(^{55,47} \) if the decelerating field was not present. Additional relations required are:

\[
a_z = \frac{e(V_m - V_o)}{md} \]

\[
r_o = r_t + 2d \sin \theta_p
\]

\[
t' = \sqrt{\frac{2mV_m}{e(V_m - V_o)^2} \, d \cos \theta_p} \left[ 1 - \sqrt{1 - \frac{(V_m - V_o)}{V_m \cos^2 \theta_p}} \right]
\]
\[ v_r = \sqrt{\frac{2eV_m}{m}} \sin \theta_p \quad v_{sp} = \sqrt{\frac{2eV_m}{m}} \cos \theta_p \]  

Where:
- \( V_m \) = mesh potential
- \( V_s \) = target surface potential
- \( m \) = electron mass
- \( r_s \) = radius of beam spot without space charge
- \( d \) = mesh to target distance
- \( \theta_p \) = angle of incidence of peripheral electrons with mesh

We can now determine \( \Delta r \) as a function of \( l, V_m, V_s, d, \theta_p \) and \( r_s \).

The worst case condition for space charge occurs when \( l \) is large, \( r_s \) is small and \( V_s \) is small. We will therefore calculate \( \Delta r \) for 1000 line cardiac cine in the 4.5" zoom mode. Values used in the calculation are \( l=1.6 \mu A, V_m=1000 \text{ V}, V_s=0.02 \text{ V}, d=2 \text{ cm}, \theta_p=0.15^\circ \), and \( r_s=62 \mu m \) (920 active lines in 4.5"). Intermediate values are \( t'=2.1254\times10^9 \text{ s}, v_r=4.9093\times10^4 \text{ m/s}, v_{sp}=1.8752\times10^7 \text{ m/s}, a_c=8.791\times10^{13} \text{ m/s}^2 \) and \( r_s=1.6672\times10^4 \text{ m} \) which yield a final \( \Delta r=11.2 \mu m \). Space charge has thus expanded a nominal 125 \( \mu m \) diameter beam spot to 147 \( \mu m \).

In the worst case condition described the space charge spreading of the beam may be tolerated but is not negligible. If higher beam currents or smaller spot sizes are required then vidicon modifications to reduce space charge will be required.

Three methods of alleviating space charge spreading are increasing \( \theta_p \), decreasing \( d \) or increasing \( V_m \). \( \theta_p \) may be increased if care is taken with respect to deflection defocusing as described earlier. Decreasing \( d \) has associated with it an increase in amplifier noise due to the increased mesh to target capacitance. This is tolerable as long as sufficient SNR can be maintained.

The best alternative is to increase \( V_m \) which in the absence of a suppressor mesh has no major side effects. If the vidicon does contain a suppressor mesh then changes in \( V_m \) or \( d \) may require a change in the position of the suppressor mesh with its associated consequences.

Overall space charge spreading can be kept small in standard fluoroscopy and cardiac cine applications as long as the deceleration field in front of the target is kept high. Space charge spreading is a major limiting factor however in achieving higher beam currents and small spot sizes.
e) **Lens Abberations**

Ideally the lens system of a vidicon should produce a perfect image of the crossover or G2 aperture on the target. Abberations in real lens systems however prevent this from happening. In general lens abberations are negligible for electrons which travel close to the lens axis (paraxial) and become important as the beam diameter increases. Small lens abberation and high beam current are therefore contradictory requirements. Various types of abberations caused by the lens are shown in Figure 14. Aberrations caused by deflection are treated in the next section. Lens abberations can be classified as geometrical or chromatic. Geometrical abberations are due to lens geometry and non ideal lens action while chromatic abberations are caused by a spread in the energy of electrons. In a vidicon the lens is almost always axially symmetric. Perfectly machined axially symmetric lenses however still have abberations. These abberations have been studied extensively and can be categorized mathematically into third order, fifth order, and higher odd orders\(^{36,57,44}\). In a vidicon abberations of the spot should be small enough that only third order or Seidel abberations need be considered.

There are five Seidel abberations: spherical abberation; astigmatism; coma; curvature of field; and distortion. In addition to the abberations of a perfect axially symmetric lens, abberations can occur due to imperfections or asymmetries in the lens. These are called parasitic abberations, the most important of which is axial astigmatism. These abberations will now be considered separately.

Spherical abberation is the most important of the geometrical lens abberations in a vidicon\(^ {19,30,44}\). It is the only Seidel abberation that occurs for object points on the axis. Since the crossover or G2 aperture is very small compared to the lens it can be considered to be a point object on the axis. Spherical abberation occurs because electrons which travel through the lens at some distance from the axis experience stronger focusing than paraxial electrons and focus at a point in front of the target (see Figure 15). Unlike light optics, spherical abberation in electron optics cannot be corrected with additional lenses since it is not possible to make a lens in which the focusing strength decreases away from the axis. The best way to reduce spherical abberation is to make the lens physically larger. A rule of thumb is that the beam width
Figure 14. Lens aberrations.

Figure 15. Spherical aberration caused when the outer electrons in the lens experience stronger focusing than paraxial electrons causing them to focus before the target.
in the lens should be no more than 1/10 of the lens inside diameter\textsuperscript{58}. In general, practical magnetic lenses tend to have lower spherical aberration than electrostatic lenses mostly due to the fact that the magnetic lens being on the outside of the tube tends to have a larger clear diameter\textsuperscript{40}.

When paraxial electrons are focused to a point on the target the non-paraxial electrons form a blur around this point with a diameter of $d_s$. Directly in front of this point many electron paths cross the axis before reaching the target as shown in Figure 15. The point in front of the target with the smallest overall beam diameter is called the disc of least confusion. It can be shown that the disc of least confusion\textsuperscript{59,44,45,57} has a diameter of $d_{LC}=(1/4)d_s$. A 4 times improvement in spherical aberration therefore occurs when the disc of least confusion is made to focus at the target. Spherical aberration increases as the third power of the beam diameter inside the lens which means that it also increases as the third power of the beam semiangle $\theta_p$. Spherical aberration is given by\textsuperscript{46}:

$$d_s = \frac{1}{4}S_s d_a^3 = 2S_s b^3 \theta_p^3$$

(22)

Where:

- $d_s = \text{diameter of blur (assuming paraxial focus at target)}$
- $S_s = \text{spherical aberration constant}$
- $d_a = \text{diameter of beam inside the lens}$
- $b = \text{lens to target distance}$

Values of $S_s$ for an einzel lens are given by Ramberg\textsuperscript{60,56} as shown in Figure 16. Assuming the aberration of his lens to be representative of most einzel lenses we can calculate the spherical aberration to be expected in a large area vidicon.

For our calculation we will assume a system with $a=10$ cm, $b=50$ cm, $f=8.33$ cm, $d_a=2.6$ mm, and $\theta_p=2.6$ mrad (0.15°). For an einzel lens of inside diameter $D=1.5$ cm we get $D/f=0.18$ which from the graph tells us that $[(V_f-V_0)/V_f]^2 = 0.43$. For $V_f=300$ V the focus potential $V_0$ is thus 103 V. Also from the graph we find $(S_sD^2)/M=3.2$ which gives $S_s=0.071$ mm$^2$. From Equation 22 $d_s=(0.25)(0.071)(2.6)^3=0.31$ mm. If we focus for the circle of least confusion we get $d_{LC}=d_s/4=78 \mu$m.

Spherical aberration for a short magnetic lens can be estimated from the graph in Figure 17 by Ramberg\textsuperscript{56,60}. Assuming the same parameters used above except that the lens inside diameter is now $D=3.5$ cm we get $D/f = 0.42$. From the graph $(S_sD^2)/M = 3.2$ which gives $S_s = 0.013$ mm$^2$ and $d_{LC}=14.2$ \mu m. The magnetic lens can therefore provide a much lower spherical aberration if the einzel lens proves to be inadequate.
Figure 16. Spherical aberration constant for an einzel lens. (from Ramberg⁷⁰)

Figure 17. Spherical aberration constant for a short magnetic lens. (from Ramberg⁷⁰)
The remaining four spherical aberrations (coma, astigmatism, curvature of field and distortion) are all off-axis aberrations which means that unlike spherical aberration they do not occur for object points on the axis. These aberrations therefore do not occur in a properly aligned electron gun. Most electron guns, however usually require some degree of alignment by the use of small magnets near the G1 and G2 electrodes. It is important therefore to be able recognize these aberrations of a misaligned gun.

Coma is similar to spherical aberration in that it is caused by electrons travelling closer to the periphery of the lens and experience stronger focusing. Instead of causing a circular blur, however, the off axis point is imaged as a distinctive comet or tear drop shape. (see figure 18)

Astigmatism occurs when electrons travelling in a given plane have a focal point which is different from electrons travelling in a perpendicular plane. (see figure 19) The beam has two focal positions where the electrons focus along a line. As the beam is focused the image spot changes shape. Over its full range the spot goes through the shapes: elliptical, line, elliptical, circular, elliptical at 90°, line at 90°, elliptical at 90°.

Curvature of field occurs when off-axis objects form an image surface which is not in a plane. The image spot is of such a small size compared to the target, however, that this aberration is negligible even in a misaligned gun. The lens curvature of field should not be confused with the deflection curvature of field which is a significant problem.

Distortion occurs when lens magnification changes as an object point moves away from the axis. Distortion appears as either pincushion distortion or barrel distortion depending on whether magnification increases or decreases away from the axis. Since the change in magnification is usually small, distortion is not a concern even in a misaligned gun. Again lens distortion should not be confused with deflection distortion which is a significant problem.

Axial astigmatism as distinct from astigmatism is a parasitic aberration, that is it occurs in lenses which are asymmetrical or "out of round". Asymmetries in a lens can cause a wide variety of complicated aberrations. In a vidicon the asymmetry of most concern occurs when a circular lens element is slightly flattened or elliptical. The most troublesome effect of this defect is an astigmatism which unlike regular astigmatism affects object points on axis. To prevent axial astigmatism the parts of a lens must be
Figure 18.  Coma of the electron beam spot. This aberration is similar to spherical aberration but for off-axis points.

Figure 19.  Astigmatism of the electron beam spot. This aberration occurs when the lens has unequal horizontal and vertical focal lengths.
 machined very accurately. The most critical parts are those in the vicinity of the strongest focusing fields. Leaman\textsuperscript{19} cites as an example that an out of round distortion of 0.004" in a 0.750" diameter electrode would render a 1" vidicon unusable. Moss et al\textsuperscript{61} has studied the effects of elliptical deformation in lens elements. For the electrostatic lens he studied he found the maximum tolerable difference in the major and minor axes was 0.2 mm in a nominal 25 mm diameter. These examples show that a machine tolerance in roundness of 1 part in 200 or better is required on critical lens elements.

Chromatic abberation is important in vidicons since like spherical abberation it occurs on axis. It is caused by the spread in electron axial velocities in the beam which in turn causes a spread in the focal position. The spread in energy due to thermal emission at the cathode is given by $\Delta E = kT/e$ which for $T=1100K$, $k=1.38x10^{-23}J/K$ and $e=1.6x10^{-19}J/eV$ gives $\Delta E = 0.1 eV$. This value is achieved for diode guns. However, in triode guns, space charge effects near the crossover cause the energy spread to increase and an effective value of $\Delta E = 0.2 eV$ is commonly assumed\textsuperscript{62,64}. Various lenses have different degrees of susceptibility to chromatic abberation characterized by the quantity $(df/dV)(V/f)$ which is a measure of the change in focal length as a function of electron energy.

For einzel lenses and short magnetic lenses the diameter of the blur due to chromatic abberation is given by\textsuperscript{30}:

$$d_c = 2 \frac{df}{dV} (1+M)^2 \Delta V \theta_p$$

Where:
- $d_c =$ diameter of blur caused by chromatic abberation
- $f =$ focal length
- $V =$ potential of image and object space
- $M =$ magnification
- $\Delta V =$ electron energy spread (V)
- $\theta_p =$ beam semiangle at image

Chromatic abberation of a short einzel and short magnetic lens\textsuperscript{30,56,60} are shown in Figure 20. From Figure 20 an einzel lens under worst case conditions ($V_o=0$) has a chromatic abberation of $(df/dV)(V/f)=4$. For a large area vidicon with $f=83$ mm, $V=300$ V, $\Delta V=0.2$ V, $M=5$, and $\theta_p=2.6$ mrad (0.15") we find $d_c=41.4 \mu m$. Figure 20 also gives the chromatic abberation for a short magnetic lens as $(df/dV)(V/f)=0.7$ over a wide range of lens current. Using the same conditions as the einzel lens the spread of the beam spot is only $d_c=7.3 \mu m$ which is negligible.
Figure 20. Chromatic aberration of a short einzel and short magnetic lens. (adapted from Ramberg60)

Figure 21. Magnetic deflection in a homogeneous field.
Overall lens aberrations can be kept low as long as \( \theta_p \) is kept small, accelerating potentials are kept high, parts are accurately machined and the gun is well aligned. If a larger \( \theta_p \) is required the lens may need to be made larger.

1) **Deflection Abberations**

Electromagnetic deflection is generally preferred over electrostatic deflection in short focus and deflection raster scanned systems due to its lower abberations especially for large deflection angles. The main reason for this is that electrons travelling near the positive plate in an electrostatic deflector are at a higher potential and thus higher velocity than those near the negative plate. The higher velocity electrons are deflected less and improper deflection occurs. In contrast magnetic deflection occurs in an region of uniform potential and abberations are less. We will therefore concern ourselves only with magnetic deflection.

Similar to abberations in the lens, deflection abberations can be divided into three main categories: homogeneous, non-homogeneous, and chromatic. Homogeneous abberations are those that occur even if the deflecting field is homogeneous and free of fringing fields. Non-homogeneous abberations are due to either fringing fields or non-uniformities (parasitics) and chromatic abberations are due to the energy spread of electrons.

Ideally we would like the electron beam when deflected to always focus in the target plane and the deflection distance to be proportional to the deflection current. This, however, does not occur even if the magnetic field is perfectly homogeneous. Figure 21 shown a beam of electrons experiencing a homogeneous magnetic deflection field of fixed axial extent. Within the field each electron follows a circular curve of fixed radius. The deflected paths can then be found by simple geometry. The curvature of field and associated astigmatism are readily apparent and represent the most important deflection abberations. These abberations are also known as deflection defocusing.

The diameter of the defocused spot \( (d_p) \) is given by:

\[
d_p = \lambda^2 Z \theta_p = \frac{\lambda^2 d_o}{2}
\]  

(24)
Where:  
\( \lambda \) = deflection angle from the central axis  
\( Z \) = deflection to target distance  
\( \theta_p \) = beam semiangle  
\( d_s \) = diameter of beam in deflection field

Assuming a large area vidicon with 9" diameter target, \( z=50 \text{ cm} \), and \( \theta_p=2.6 \text{ mrad } (0.15^\circ) \) we find \( \lambda=0.22 \text{ rad} \), \( d_s=2.6 \text{ mm} \) and thus \( d_{0}=62.9\mu \text{m} \). The nominal spot size for 1000 scan lines (920 active) in 9" is \( d_{15}=250 \mu \text{m} \). Deflection defocusing thus causes a noticeable increase in spot size at the edges of the scan. This loss of corner resolution is a well known phenomenon in vidicons. The centre of the image is not affected.

Deflection defocusing can be reduced by decreasing \( \theta_p \) or \( \lambda \) but this can only be done at the expense of beam current or by increasing tube length. Fortunately much of the defocusing blur can be considerably reduced by dynamic focusing. By applying a time varying voltage to the focus electrode of the gun (or focus coil current) the circle of least confusion can be made to focus at the target at all times. This technique has been successfully employed in vidicons and CRT's\(^{63,24,25,32}\).

Another aberration of homogeneous deflection is raster distortion in the form of pincushion distortion. This distortion occurs because of a small added deflection when \( \lambda \) becomes large thereby stretching the scan pattern at the periphery. A pincushion distortion in the vidicon will actually appear as a barrel distortion on the viewing CRT. Distortions can be corrected by the use of permanent magnets or DC coils placed around the tube or by time varying the deflection currents\(^{35}\).

Associated closely with the deflection is the corrector or collimator lens which bends the beam perpendicular to the target. The barrel distortion of this lens can be used to help correct pincushion distortion\(^{30,35}\). Other aberrations caused by this lens and their possible corrective application requires further investigation.

Non-homogeneous deflection fields can occur due to fringing fields or by manufacturing inaccuracies. This causes aberrations due to the fact that different parts of the beam experience a different field. These aberrations can be quite complex and include astigmatism, coma, curvature of field, and distortion. Fortunately magnetic deflection does not introduce any additional spherical aberration\(^{64}\). Fringe fields are reduced by adjusting the shape and winding distribution in the deflection coil. The complexity of the problem usually means that the best configuration is found by trial and error.
Chromatic aberration in magnetic deflection will be negligible since deflection is proportional to \((1/V)^{1/2}\) and electron energy spread \(\Delta V/V\) is only about 1 part in 5000 \((0.2V/1000V)\), making the deflection error 1 part in 10,000 \(((1+\Delta x)^{1/2} - 1+\Delta x/2)\).

**g) Self Sharpening**

When an electron beam scans the surface of the target it does so in an asymmetrical fashion in the sense that the beam has a leading edge and a trailing edge and lies between that part of the target which has been read and that part which is yet to be read. If more of the signal current is contributed by the leading edge of the beam rather than the trailing edge then the effective spot size will be reduced. This effect is called self sharpening\(^{62,65,15}\). Kurashige\(^{66}\) has studied the effect and finds a wide variety of beam spot shapes depending on beam and target conditions. A summary of his general findings are:

1) Self sharpening decreases as target capacity is increased.
2) Self sharpening decreases with increasing energy spread in the beam.
3) Self sharpening increases with signal current but then decreases as signal current approaches the beam current.
4) Self sharpening decreases as \(\theta_p\) is increased.
5) Self sharpening increases as beam current increases.

For a given large area vidicon with target layer capacitance \(C_T\), \(\Delta V\), \(\theta_p\), and beam current \(i_b\) fixed, the self sharpening effect will vary with signal current with the maximum effect occurring at a signal current intermediate between zero and \(i_b\). The reduction in spot width can be as much as a factor of 2. While this reduction in spot size is welcomed, we will not rely upon it in the design of the vidicon since the signal current dependence adds complication.

**h) Comparison of Defocusing Effects**

A summary of defocusing effects and values for worst case conditions are shown in Table 2. Image defocusing even at large signal levels is small so that at average signal levels it is negligible. Space charge defocusing, spherical aberration and chromatic aberration are also acceptably small. Deflection defocusing at the edge of the image is the largest effect but can be significantly reduced by using dynamic focusing.
<table>
<thead>
<tr>
<th>Defocusing Effect</th>
<th>Worst Case Condition</th>
<th>Nominal Spot Diameter for Worst Case</th>
<th>Increase in Spot Diameter for Worst Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image Defocusing</td>
<td>1000 line 4.5&quot; 620 nA signal</td>
<td>125 µm</td>
<td>14 µm (11.2%)</td>
</tr>
<tr>
<td>Space Charge Defocusing</td>
<td>1000 line 4.5&quot; 2 µA beam</td>
<td>125 µm</td>
<td>22.4 µm (17.9%)</td>
</tr>
<tr>
<td>Spherical Abberation (Magnetic Lens)</td>
<td>1000 line 4.5&quot;</td>
<td>125 µm</td>
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<td>1000 line 4.5&quot;</td>
<td>125 µm</td>
<td>7.3 µm (5.8%)</td>
</tr>
<tr>
<td>Deflection Defocusing</td>
<td>1000 line 9&quot;</td>
<td>250 µm</td>
<td>62.9 µm (25.2%)*</td>
</tr>
</tbody>
</table>

*At edge only, no dynamic focusing

Table 2. Increase in beam spot diameter for various electron beam defocusing effects under worst case conditions.

6) **Beam Bending**

The presence of a charge image on the target surface implies the presence of lateral electric fields in the deceleration space of the vidicon. These lateral fields can cause bending of the beam toward the more positive parts of the image.

It can be shown that the relative beam bending in a large area vidicon is the same as that of a 1" vidicon. Since we assume a large area vidicon with the target diameter, image dimensions, and the mesh spacing to be a factor $K$ larger than in a 1" vidicon and we also assume the image potentials and the mesh potential to be the same as the 1" vidicon then the electrons paths must also be the same as in a 1" vidicon scaled by a factor of $K$. The image potentials will be the same as the 1" vidicon if the target layer capacitance and signal currents are also the same. This is approximately true for the $a$-Se layer we have
been considering. Since beam bending does not pose significant problems in the 1" vidicon of an XRII/TV system this should also be the case in large area vidicon.

The actual amount of beam bending in a large area vidicon can be calculated in the same fashion as space charge spreading was estimated. Assume that electrons travel from the mesh to target unaffected by lateral fields. Determine the lateral force that would exist on the electron at each point in the path. Then calculate the deviation that this force would have on the electron.

We will assume half the target to be at a surface potential of zero and the other half to be at a potential of $V_s$. The potential between these two regions changes linearly along a line of width $X_o$. The lateral electric field directly above this line is given approximately by:

$$E_x = \frac{V_s}{\frac{1}{2}(2\pi y) + X_o}$$  \hspace{1cm} (25)

Where:  
$E_x$ = lateral electric field  
$V_s$ = surface potential  
y = distance above surface  
$X_o$ = width of potential transition region

The geometry for this problem is shown in Figure 22. The path of undeviated electrons is given by:

$$y = d - \sqrt{\frac{2eV_m}{m} t + \frac{1}{2} \frac{eV_m t^2}{md}}$$  \hspace{1cm} (26)

Where:  
d = mesh to target distance  
$V_m$ = mesh potential  
t = time ($t=0$ at mesh)  
m = electron mass

Using Equations 25 and 26 the deviation for electrons landing on the line is:

$$\Delta x = \frac{eV_m}{m \pi} \int_0^l \int_0^l \frac{1}{d + \frac{X_o}{\pi} \sqrt{\frac{2eV_m t + 1}{m} \frac{eV_m t^2}{2 md}}} dt \, dt$$  \hspace{1cm} (27)
Figure 22. Beam bending caused by a region of positive surface potential.

Figure 23. First Scan MTF due to the Krittman effect with 500 μm thick a-Se layer.
Using values of $V_s=2$ V, $V_m=1000$ V, $d=2$ cm, and $X_0=125$ μm (1 pixel width) we find $\Delta x=79$ μm. This shift is less than 1 pixel width for a very sharp transition in surface potential corresponding to a signal transition of 0 to 620 nA. This example shows that the shift and edge blur in the image due to beam bending is negligible for the expected signal currents in standard and cardiac fluoroscopy.

A situation where significant beam bending can occur is when an area of the target is exposed to x-rays but is not in the region of scanning. The high potential developed in the unscanned region can pull the beam toward it. The beam should then always overscan the x-ray region or else a flood beam with its cathode a few volts above ground should be used to limit the rise in surface potential.

Another situation where beam bending could cause problems is in DSA. Large signal currents can give rise to large surface potential changes and thus beam bending over several pixels. To alleviate this the mesh would need to be moved closer during the DSA run. Another side effect of beam bending is that the beam does not land perpendicularly to the surface. This can cause lag problems which are discussed later.
7) **Krittman Effect**

When an electron beam scans the surface of a photoconductor it is the surface potential rather than charge that determines whether beam electrons will land. A positive point charge on the surface raises the potential of the surface in its vicinity. The extent of this potential distribution therefore represents a blur in the readout process. This is called the Krittman effect\(^{68,69,62,70}\).

The amount of potential blurring increases as the photoconductor is made thicker. Since surface charge couples to the target electrode on the opposite side of the layer, blur is roughly of the same order as the photoconductor thickness. Since the photoconductor of an x-ray vidicon must be made thick the Krittman effect represents a serious limitation to resolution. To a first approximation a large area x-ray vidicon has a target which is 10x greater in diameter than a 1" vidicon but its photoconductor is 100x thicker. The relative Krittman effect is therefore 10x worse in the large area vidicon.

Krittman has calculated the first scan MTF for the effect. His method involves calculating the potential distribution for a line of charge on the surface and then taking the Fourier transform of this potential along a line perpendicular to the line charge.

The resulting MTF is given by\(^{68}\):

\[
MTF(f_s) = \frac{1-e^{-4\pi f_s x}}{4\pi f_s x}
\]  

(31)

Where:
- \(f_s\) = spatial frequency (lp/mm)
- \(x\) = photoconductor thickness (mm)

The dependence of MTF on photoconductor dielectric constant has been found negligible by Krittman and does not appear in this expression. This MTF has been calculated for a 500 \(\mu\)m thickness of \(\alpha\)-Se and is shown in Figure 23. The severity of MTF loss is readily apparent.

While Equation 31 provides a useful approximation to the MTF, the actual MTF is more complicated. Equation 31 assumes that the beam will deposit charge in proportion to the pre-scanned potential distribution. In reality the potential distribution changes as the beam scans and will in general deposit more charge on the leading edge of a positive charge distribution than on the trailing edge. The MTF is therefore better than the approximation of Equation 31 would indicate but is still quite poor.
Fortunately the Krittman effect is a transient effect since, in equilibrium, the charge deposited by the beam in one frame at a given point must equal the charge developed in the photoconductor in one frame at that same point. When a static image first appears on the target, the first scan will be blurred due to the Krittman effect. Negative charge deposited in the first scan however, modifies the potential distribution of the replenished positive image charge in the second scan. The second scan is much sharper and more closely approximates the image charge distribution. In experiments described by Krittman no significant improvement in sine-wave response is observed after the third scan. This transient behaviour is illustrated in Figure 24.

For real time readout the Krittman effect will cause moving objects to appear to have lag. Unlike normal "signal lag" which is a delay in achieving a new equilibrium signal level, the Krittman effect will cause a "resolution lag" which may be much less disturbing.

For single frame exposure and readout a number of methods could be invoked to reduce the Krittman effect:

1) Use a thinner, higher Z photoconductor. One must remember however, that if layer capacitance is made too high, beam discharge lag will result.

2) Deconvolve the image with the first scan point spread function. Deconvolutions of course have a noise penalty.

3) Follow the first scan x-ray readout with 3 or more scans each with the cathode potential a volt or two higher than the previous scan. These subsequent scans will be flat except for the high frequency information lost in the first image. A method similar to this is described by Doughty\(^7\). For high x-ray exposures the electronic noise added by the subsequent scans will be below x-ray quantum noise.

4) Use a return beam readout with a close mesh. A target to mesh spacing of 0.1 mm will limit image potential blur to the same order. This close mesh spacing is not detrimental to the return beam readout.

The Krittman effect requires further investigation both theoretically and experimentally. Present indications are that the effect will cause a minor lag in fluoroscopic images but single exposure readout will require some modification of the vidicon structure or readout process.
Figure 24. Transient Krittman effect.
8) **High Velocity Readout**

Normal vidicon operation involves the electron beam depositing electrons on the surface in response to positive surface charge created by photoconduction. This mode of operation is called cathode stabilization since the photoconductor surface in equilibrium will be near cathode potential. An alternate mode called anode stabilization is also possible where beam electrons land with enough velocity to release secondary electrons. The loss of electrons from the surface causes positive surface charging toward mesh (anode) potential. Anode stabilization or high velocity readout is described further in chapter 4.

High velocity readout is in general capable of higher resolution than normal low velocity readout. Since electrons are not slowed to near zero velocity the effects of space charge, beam deceleration, self sharpening, and beam bending are greatly reduced. Beam discharge lag is also greatly reduced allowing high capacity targets to be used. Unfortunately redistribution of secondary electrons and non-uniform secondary emission plague this mode of operation and a completely satisfactory solution has yet to be found. Dresner has produced a high velocity vidicon with greatly reduced redistribution effects. If the problems of redistribution and uniformity could be solved the advantages of high velocity readout would be great.

B) **LAG**

The word lag loosely refers to any residual effect from a previous frame or frames that corrupts the current frame. More specifically lag refers to any temporal effect lasting less than one second causing a smear or tail behind a moving object. Long term effects which leave a persistent image lasting more than a second are referred to as burn-in or sticking. Lag or burn-in stems from three main sources. The first of these are beam discharge effects in which electron energy spread in the beam or non-perpendicular landing reduce the ability of the electron beam to faithfully readout the signal charge. Second is the photoconductor in which trapping plays a major role and third, the Krittman effect can cause a short term lag as was mentioned earlier.

In vidicons, turn-off lag (white to black) is generally always slower than turn-on lag (black to white) and is more often measured and studied. The most common measurement of lag is the percentage of residual signal that exists 50 ms or 3 television fields (TVF) after illumination is removed. Removal of illumination is synchronized to occur immediately after the measured spot is scanned in the zeroth field. It is also common to measure lag in the 10th or 12th field to detect the presence of a long tail. Lag
usually appears as a monotonic change in signal from the initial to final level and is referred to as positive lag. Negative lag is also possible and occurs when the transient signal overshoots or undershoots the new equilibrium signal level. While lag is generally considered undesirable, in some fluoroscopic procedures it can be used to increase SNR by integrating quantum noise as mentioned in Chapter 2. For maximum flexibility the large area vidicon should be designed for low lag and any noise integration performed externally.

Beam discharge lag, non-perpendicular landing and photoconductive lag will now be examined.

1) **Beam Discharge Lag**

If the electron beam in a vidicon were monoenergetic then it would deposit electrons as long as the photoconductor surface was positive and stop immediately when the surface became zero (cathode at 0V). In reality the electron beam contains a distribution of energies spread around some mean. Charging does not end abruptly when the photoconductor surface reaches zero because the more energetic electrons are still able to land. As the photoconductor surface becomes more negative, an decreasing percentage of the beam current continues to land. The surface would slowly continue to charge negative in the dark if it were not for the existence of small leakage currents that come into equilibrium with the beam\(^{65}\).

The source of the energy spread is the Maxwellian distribution of thermionically emitted electrons from the cathode. For a typical oxide cathode at 1100K the energy spread is about \(kT/e\sim 0.1\) eV. An additional energy spread can also occur due to space charge interactions in the crossover of a triode gun\(^{14,20}\). A triode gun typically has a total energy spread of about 0.2 eV while a diode gun is close to the thermal value of 0.1 eV.

The ability of the beam to charge the photoconductor is given by the beam acceptance curve (Figure 25). This curve gives the beam current that lands on the on the target as a function of the surface potential. This will include the effects of electron energy spread as well as secondary electron emission at the surface. The curve has three regions\(^{76,65}\) known as the Maxwellian, linear and secondary emission regions.
Figure 25. The beam acceptance curve.

Figure 26. Target surface potential transient in beam discharge lag.
The beam current accepted by the target in the Maxwellian region is given by:

\[ I_a = I_b e^{\frac{V_s}{\Delta V_b}} \]  \hspace{1cm} (32)

Where:\n\[ I_a = \text{accepted beam current} \]
\[ I_b = \text{beam current} \]
\[ \Delta V_b = \text{energy spread in the beam} \]
\[ V_s = \text{surface potential} \]

This equation measures the current due to the most energetic electrons in the tail of the Maxwell distribution. For \( V > 0 \) the acceptance curve displays a linear region and a few volts above this secondary emission reduces beam acceptance. In normal operation only the Maxwellian and linear regions are used.

At any given \( V \), a beam resistance \( R_b \) may be defined as the slope of the beam acceptance curve \( R_b = \Delta V / \Delta I_a \). In the linear region \( R_b \) is the lowest and charging occurs rapidly. The Maxwellian region has higher \( R_b \) and therefore creates more lag. For simplicity the beam acceptance curve is usually modelled theoretically with a Maxwellian region for \( V < 0 \) and a constant current \( I_a = I_b \) region for \( V > 0 \).

During operation the surface potential is constantly rising due to illumination and is being periodically reduced by the beam. For a fixed illumination the rise in potential per frame \( \Delta V \) is fixed but the reduction by the beam depends on \( V \). In equilibrium the surface potential will adjust itself until \( \Delta V \) for illumination equals \( -\Delta V \) for beam discharge. When illumination level changes the surface finds a new equilibrium. This is illustrated in Figures 25 and 26. Points A and B are for strong illumination with point A being the potential just before the beam passes over and point B being the potential just after. Surface potential therefore oscillates between A and B in equilibrium. With reduced illumination the surface finds new equilibrium potentials C and D. The transition involves many intermediate values which represent lag.

The transient current that occurs in the transition from initial current \( I_1 \) to final current \( I_2 \) can be calculated easily using Equation 32 along with:

\[ I_s - I_2 = C \frac{dV}{dt} \]  \hspace{1cm} (33)
and:

\[ I_a = I_1 \text{ at } t = 0 \]  

which gives:

\[ I_a = \frac{I_2}{1 - \left(1 - \frac{I_2}{I_1}\right)e^{-\frac{t}{\tau}}} \quad \tau = \frac{C\Delta V_b}{I_2} \]  

The expression for the time constant tells us some important information about lag. First, lag is independent of the beam current \( I_b \) (assuming \( C, I_1, \) and \( I_2 \) constant) which at first seems counterintuitive. It can be understood by considering the fact that if beam current is increased the equilibrium surface potential becomes lower. So although higher beam current means fast charging, the surface is charged to a lower potential and ends up taking the same time. This beam current independence applies only to the Maxwellian region and not the linear region, but most of the lag occurs in the Maxwellian region.

Beam discharge lag can be reduced by three methods: 1) Decreasing target capacitance \( C \) (assuming \( I_1 \), and \( I_2 \) constant), N.B. Too low a value of \( C \) will lead to beam bending problems; 2) Decreasing \( \Delta V_b \), by using a diode rather than a triode gun; and 3) Increasing the final current \( I_2 \) (assuming \( C \) and \( I_1 \) constant), using a bias light (a uniform illumination\textsuperscript{17,11,21,32} of the target). The bias current produced can be easily subtracted in the video amplifier chain. This technique is commonly used to reduce lag in optical tubes e.g. Saticons and Plumbicons.

To a first approximation a large area \( a \)-Se x-ray vidicon will have the same beam discharge lag as a 1" \( a \)-Se vidicon. If we assume the \( a \)-Se diameter to be 10x larger (.9" to 9") and the \( a \)-Se thickness to be 100x larger (5 \( \mu \)m to 500 \( \mu \)m) then the target capacitance will be unchanged. Assuming also identical beam energy spread and scan parameters then beam discharge lag will be the same. Equation 35 can be used to estimate the expected beam discharge lag under various conditions. The percentage of residual signal for a white to black transition is given by:

\[ \text{Lag} = \frac{I_a(t_f) - I_2}{I_1 - I_2} \]  

Where: \( t_f \) = frame time
Lag expressed as a fraction of the signal can be reduced by increasing the signal \((I_f-I_s)\) even though the absolute level of lag is relatively unchanged. It is important therefore, when quoting a figure for lag that the signal level \((I_f-I_s)\) and bias level \((I_s)\) also be given. Unfortunately, there is no standard value of signal current or bias current at which lag is quoted. Lag values of light sensitive vidicons can be found for signal currents ranging from 10 nA\(^{(78)}\) to 500 nA\(^{(14,79)}\) and bias currents from 0 nA to 20 nA. Lag values quoted for signal currents in the range of 200 nA to 400 nA are common since this corresponds to the average signal currents used in broadcast applications.

For our calculation we will assume a white signal of 300 nA and a bias of 20 nA which gives \(I_f=320\) and \(I_s=20\) nA. We will also consider both a 9" diameter and 4.5" diameter field of view which are overscanned. Overscanned means that the circular x-ray region fits just inside the 4:3 rectangular scan area. The ratio of circular area to rectangular area is 0.59 and the ratio of active to total scan time is 0.75. Lag is calculated at 50 ms or the third field. The value of \(t_f\) in Equation 36 is therefore \((50\text{ ms})\times(0.59)\times(0.75)=0.022\) s. The results are shown in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>9&quot; diameter</th>
<th>4.5&quot; diameter</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>(C = 4.3) nF</td>
<td>(C = 1.1) nF</td>
</tr>
<tr>
<td>Triode Gun</td>
<td>8.6%</td>
<td>0.9%</td>
</tr>
<tr>
<td>(\Delta V = 0.2) eV</td>
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<tr>
<td>Light Bias = 20 nA</td>
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<tr>
<td>Diode Gun</td>
<td>3.5%</td>
<td>0.1%</td>
</tr>
<tr>
<td>(\Delta V = 0.1) eV</td>
<td>\</td>
<td></td>
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<tr>
<td>Light Bias = 20 nA</td>
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Table 2. Estimate of beam discharge lag in a large area x-ray vidicon. (500 \(\mu\)m \(\alpha\)-Se, overscanned, \(I_f=320\) nA, \(I_s=20\) nA).

From the table it can be seen that lag varies greatly with scan size. According to van de Polder\(^{77}\) for broadcast purposes lag in the third field should be less than 5\% for a peak white to black transition. This criterion can be met for the 9" diameter field of view by the use of a diode gun. For the 4.5" diameter field of view beam discharge lag is much lower and well within our criterion regardless of gun type. It should be noted that Table 2 gives the lag only for a given value of \(I_f\) and \(I_s\). Lag in a particular image however will vary over the image depending on local values of \(I_f\) and \(I_s\).

For comparison, some typical lag values for light sensitive vidicons are: A 1" \(\text{Sb}_2\text{S}_3\) vidicon for XRII use
(EEV 842X) with a 300 nA signal current and a 20 nA bias current, has 18.5% lag in the third field. A 1" Chalnicon\textsuperscript{80} (Toshiba E5022) with a 400 nA signal and 2 nA bias current, has a lag of 8% in the third field and a lag of 10% for a 200 nA signal and 2 nA bias. A 1" diode gun Saticon\textsuperscript{79} has a third field lag of less than 1% for a signal current of 500 nA and 6% third field lag for 50 nA signal and no bias.

2) \textbf{Non-Perpendicular Beam Landing Effects}

In the previous section it was assumed that the beam approaches the target perpendicularly. This may not always be true especially near the periphery of the target. Although the collimator lens is designed to provide perpendicular landing at all parts of the target, errors of a few degrees may occur in practice. When the beam approaches the target at some angle it has a non zero radial energy and a reduced axial energy. This reduced axial energy causes the surface to stabilize in the dark at a potential above cathode potential\textsuperscript{81.77} (0V). This potential is given by:

\[ V_s = V_m \sin^2 \theta_m \]  

Where:  
- \( V_s \) = surface potential in the dark  
- \( V_m \) = potential of mesh above the surface  
- \( \theta_m \) = angle of beam as it passes through the mesh

For \( V_m = 1000 \text{V} \) and \( \theta_m = 5^\circ \) we get \( V_s = 7.6 \text{V} \). In a 1" vidicon a difference of 7.6V from the centre to the edge of the target can result in a significant non-uniformity in sensitivity\textsuperscript{34}. This is because the potential across the photoconductor which is normally 10 to 50V has been reduced by a significant amount. For this reason perpendicular landing in the 1" vidicon is very important and \( \theta_m < 5^\circ \) is required.

In a large area vidicon the target potential may be >1000V and therefore a difference of 7.6V has a negligible effect of sensitivity. The non-uniformity in sensitivity (or "shading") problem therefore is insignificant in a large area vidicon.

Non-perpendicular landing unfortunately has other detrimental effects. When a non-perpendicular beam passes through the mesh it travels laterally before landing. The potential of the target under the beam trajectory can affect the path of the beam. The two cases of importance are when the beam passes over a low potential region and when it passes over a high potential region. These two cases are shown in Figure 27.
Figure 27. Non-perpendicular beam landing effects.

Figure 28. Stern wave effect and ripple caused by non-perpendicular beam landing.
When the beam passes over a low potential region (Figure 27a) it is attracted to the positive high potential region which increases its radial velocity and decreases its axial velocity. The surface therefore stabilizes at a potential above the equilibrium dark level of $V_m \sin^2 \theta_m$. Similarly when the beam passes over a high potential region (Figure 27b), radial velocity is reduced and axial velocity is increased and stabilization occurs at a potential below $V_m \sin^2 \theta_m$.

A problem attributable to the above described phenomenon is the helgolf or stem wave effect\textsuperscript{77,81}. If we consider a fixed "white" object scanned by a non-perpendicular beam we find the potential of the background next to the object can be higher or lower that the rest of the background depending on the angle of the beam. The case where the beam passes over a "white" object before landing is shown in Figure 28. The region next to the "white" object thus stabilizes at a potential lower than $V_m \sin^2 \theta_m$. As long as the image does not move no effect is noticed. When the object does move however, the low potential region is in effect uncovered and appears as a black region. In motion the object appears to be followed by this black stem wave.

Another phenomenon that can occur is persistent rippling, a wave like motion that occurs even if objects in the image are not moving. The effect occurs in severe cases (significant $\theta_m$) when positive regions tend to form more negative adjacent regions and negative regions tend to form more positive adjacent regions. During each scan, surface potentials shift and oscillation occurs. This effect can be seen at the edges of the image in Figure 24 of Chapter 5.

The stem wave and persistent rippling are damped and undamped effects of the same phenomenon. Thus both these effects can be eliminated by using a more perpendicular beam. Van de Polder\textsuperscript{77,81} recommends that $\theta_m$ should be in general less than $3^\circ$.

3) \textbf{Photoconductive Lag}

Photoconductive lag is caused by the trapping of carriers as they traverse the photoconductor. Trapping effects can be quite complex. One must consider electrons and holes both with different mobilities and lifetimes. Separate traps exist for electrons and holes and have distributions both in energy and space. Space charge formed by trapped carriers disrupts the electric field within the photoconductor, which in turn can affect blocking layers, sensitivity, carrier mobility and carrier lifetime. Trapping can cause both short term lag effects or more long term burn-in or sticking effects. Some of the common lag mechanisms will now be discussed.
Short term lag involves the temporary delay of carriers by shallow traps. A shallow trap is one which is close to the valence or conduction band and thermally releases its trapped carrier quite quickly. At any given illumination level traps are constantly being filled and emptied. An equilibrium is reached when the number of carriers trapped is such that the rate of trapping equals the rate of release. When the illumination level changes a new equilibrium has to be established. For a short time, therefore, the trap release rate may differ from the trapping rate\textsuperscript{14} thus causing lag. The release probability from a trap is enhanced by an electric field through the Frenkel-Poole effect\textsuperscript{82,83}. Lag, therefore, is reduced by increasing the electric field in the photoconductor.

Three causes of long term lag or burn-in are:

1) Trapping in a manner similar to short term lag except with deeper traps. This will cause a positive lag.

2) Deep traps which exist near the photoconductor interface can develop a space charge which either diminishes or enhances blocking\textsuperscript{17}. Leakage or dark current will therefore increase or decrease which produces a positive or negative burn-in image respectively. This image may persist even if all illumination is removed.

3) Space charge can change the sensitivity of the photoconductor, most often decreasing it\textsuperscript{94}. If the sensitivity of the photoconductor material has a sublinear dependance on electric field (such as $a$-Se) then space charge will lower the overall sensitivity of the layer. This is because the total potential across the layer is constant and an increase in sensitivity in a high electric field region does not compensate for a loss in sensitivity in a low electric field region. Unlike the dark current image, this burned in image disappears if illumination is removed.

Goto et al\textsuperscript{85} reports that the Saticon ($a$-Se vidicon) does not suffer from after images that occur when illumination is removed. This indicates that effects 1 and 2 are negligible. He does indicate, however, that negative after images occur for uniform illumination and low target potentials. This is consistent with effect 3 and a decrease in sensitivity due to space charge. This type of lag usually disappears if the target potential is raised. Photoconductive lag in thick $a$-Se layers is expected to be similar to the Saticon.

Trapping in $a$-Se depends greatly on the process used in preparing the layer and on the level of impurities. The temperature of the substrate is particularly important as is the level of certain barely detectable trace elements. Much of this information is obscure as it is maintained as a manufacturer's trade secret. Good quality $a$-Se layers tend to have a large quantity of very shallow traps, a small quantity of deep traps, and
a negligible quantity of intermediate level traps. The very shallow traps have a short time constant compared to the television frame time and so do not produce detectable lag. Their effect is mainly to change the effective mobility of the carriers. The deep traps, however, are more problematical.

The commercial Saticon tube as a high performance vidicon must have very low trapping within its a-Se photoconductor. Short term lag of the Saticon with bias light and diode gun is only about 2 or 3% for a 200 nA signal and is mainly due to beam discharge lag. While most vidicons show a level of burn-in that depends on the length of time that an intense exposure lasts, the Saticon exhibits a low level of burn-in that is relatively independent of exposure time. This means that the number of deep traps is low enough that deep trapping can become saturated. The Saticon target has progressed from the Saticon I to Saticon II and now Saticon III each with an increased resistance to burn-in. The Saticon is evidence that a-Se could have very low photoconductive lag. This high performance should also be possible in thicker x-ray layers.

The thick a-Se layers used in Xeroradiography have not been used in a real time imaging system but there is evidence to believe that they will work well. This evidence is in the fact that good quality xeroradiographic plates exhibit a low residual potential. Residual potential is that potential remaining on the photoconductor after one or more charge and discharge cycles and is due to deeply trapped charge. A low residual means a low level of deep traps.

Owing to the complexity of trapping effects, the only real way to know if a xeroradiographic plate will be acceptable is to try one in a vidicon. If a problem exists, plate process and impurity issues can then be addressed. An ideal a-Se layer should have few deep traps in the bulk and only one type of trap at each blocking interface (see Chapter 5). If both types of trap exist at an interface it is prone to barrier lowering by space charge. Also the maintenance of a high electric field in the thick a-Se layer will help to keep any photoconductive lag low.

III. CONCLUSIONS

The MTF of the 1" vidicon in an XRII/TV system will always be superior to that of the total XRII/TV MTF. A large area x-ray vidicon is expected to have the same relative MTF as the 1" vidicon and will therefore be superior to that of the XRII/TV. The greatest advantage occurs for zoom modes and when a large number of video lines is used. The MTF of the large area x-ray vidicon is mainly determined by the number of scan lines used, the beam spot profile and the bandwidth of the amplifier chain.
To minimize bulk, the preferred design of the large area vidicon is similar to that of a CRT, with the electron source and lens located in a neck and a deflection coil located where the neck meets the body. A magnetic focus coil has the lowest lens aberrations while a magnetic deflection yoke has the lowest deflection defocusing. A collimator lens is also required in the large area vidicon to make the beam land normal to the target.

Calculations were made to show that a beam spot could be achieved that was as small as the minimum line width required (1000 lines in 4.5”). Various effects tend to increase spot size over that set by imaging the electron source onto the target by a lens. The major defocusing effect in the design considered is space charge repulsion in the beam. The increase in spot size due to this effect under worst case conditions was found to be 17.9% which was considered to be acceptable. For the beam deflection of ±12.8° deflection defocusing causes an increase in spot size at the edge of the target of 25.2%. If desired this could be reduced by dynamic focusing. Spherical aberration, chromatic aberration, image potential defocusing and beam bending were also found to be within acceptable limits.

The greater photoconductor thickness of the large area x-ray vidicon can give rise to a blur in the target surface potential called the Krittman effect. This blur in surface potential causes a blur in the image. Fortunately the blur is a transient effect since the electron beam must in equilibrium respond to the surface charge distribution rather than the potential distribution. A delay of 3 scans (1/10 s) is expected for full resolution to be restored after the image is changed. This type of "resolution lag" will appear different than standard "signal lag" and it is not clear at this time if it will be bothersome.

Beam discharge lag is expected to be about the same as that of a 1" vidicon since it has approximately the same target layer capacitance. For lowest lag a diode gun and bias light are preferred as they are in the 1" Saticon and Plumbicon. Photoconductive lag in the large area x-ray vidicon is also expected to be low. Evidence for this is the low photoconductive lag of the 1" a-Se vidicon (Saticon) and the low residual potential of xeroradiographic plates to be used in the large area vidicon. A low residual potential indicates a low level of bulk trapping which causes photoconductive lag. To minimize photoconductive lag, the electric field in the a-Se should be kept above 5x10⁶ V/m which helps to quickly clear any trapping.

With lag similar to that of an XRII/TV and an MTF that is superior, the large area x-ray vidicon seems better suited to high resolution fluoroscopic applications such as cardiac cine.
REFERENCES


CHAPTER 4

THE ELECTRICAL STABILITY OF SELENIUM LAYERS
USED IN LARGE AREA X-RAY SENSITIVE VIDICONS'

1. INTRODUCTION

A large area x-ray sensitive vidicon is an alternative to the x-ray image intensifier television (XRII-TV) system for producing fluoroscopic television images. The large area x-ray sensitive vidicon is similar to a conventional light sensitive vidicon in that both use a photoconductor as the radiation detector and use a scanning electron beam for readout. In medical applications the photoconductor is required to absorb 50% or more of the incident x-rays so as not to expose the patient to unnecessary levels of radiation. When amorphous selenium (a-Se) is used as the photoconductor a thickness of ~500 μm is required. Although other x-ray photoconductors can achieve the same x-ray absorption in a thinner layer, a-Se has the redeeming advantage of having extremely low dark current, an ability to be made with uniform properties over large areas and chemical stability in air and under x-ray exposure. For proper operation, the electric field in the a-Se must be about $10^7$ V/m. For a 500 μm layer, this means a potential of 5000V is required. Such large potentials are not uncommon when a-Se is used in Xeroradiography, however, in a vidicon, this potential is extraordinary. For comparison, in a conventional 1" a-Se vidicon a thickness of 5 μm and a potential of 50V is typical.

A potential problem arises when large target potentials are used in a vidicon due to secondary electron emission. Secondary electrons are electrons emitted from the a-Se surface when bombarded by primary electrons from the readout beam. In a conventional 1" vidicon the relatively low target voltage used (50V) ensures that primary electrons will always have 50 eV or less incident energy and the number of secondaries produced will be low and will not impair proper operation.

When large target voltages are used, however, situations can arise where large numbers of secondary electrons are produced which severely disrupt normal vidicon operation. A possible method to prevent this instability is to incorporate an additional mesh into the vidicon. By analogy, with the use of meshes

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* This chapter along with chapter 6 will form the basis of a paper to be submitted to *Medical Physics* on the practical implementation of a large area x-ray sensitive vidicon.
in other kinds of tubes for the purpose of preventing the adverse effects of secondary emission, this is called a suppressor mesh. The position and potential of this mesh within the vidicon is such that it controls the motions of secondary electrons so as to prevent disruptive situations from occurring. A layer of Sb$_2$S$_3$ on the a-Se surface reduces secondary electron emission and aids the suppressor mesh.

We have shown that a suppressor mesh works successfully in both a 1" vidicon and a 6" demountable vidicon. Stable operation at target voltages exceeding 3000V were achieved.

II. BACKGROUND

A. SECONDARY ELECTRON EMISSION

When an electron strikes the surface of a material, electrons already present in the material may be knocked free. These electrons are known as secondary electrons, and the quantity produced depends on the type of material, the energy of the incident electron and the angle of incidence$^{12,3,4,5,6}$. The number of secondary electrons produced per primary electron is known as delta ($\delta$) and is given by:

$$\delta = \frac{N_{sec}}{N_{pri}} = \frac{i_{sec}}{i_{pri}}$$  \hspace{1cm} (1)

Where:

- $N_{pri}$ = average number of primary electrons
- $N_{sec}$ = average number of secondary electrons
- $i_{pri}$ = primary electron current
- $i_{sec}$ = secondary electron current

The number of secondaries produced by one primary will vary and therefore $\delta$ is a statistical average. When continuous currents are considered, $\delta$ will be the ratio of secondary to primary current. $\delta$ varies with the incident electron energy $E_i$ (or potential $V_i$, $E_i=0$ when $V_i=0$). A typical curve of $\delta$ versus $E_i(V_i)$ is shown in Figure 1. The condition $\delta=1$ is important since it separates the region $i_{sec}<i_{pri}$ from the region $i_{sec}>i_{pri}$. As $E_i(V_i)$ is increased from zero, $\delta=1$ is first encountered at an energy called the first crossover potential $E_{pri}(V_{pri})$. $\delta$ continues to increase until a maximum value $\delta_{max}$ is reached at an energy $E_{max}(V_{max})$. Above $E_{max}$, $\delta$ decreases as the penetration of primary electrons becomes larger and fewer secondaries can escape. This curve crosses $\delta=1$ once more at the second crossover potential $E_{pri}(V_{pri})$. 
Figure 1. A typical secondary electron emission curve.

Figure 2. The energy distribution of secondary electrons.
Figure 1 represents the general shape of the secondary electron emission curve for all materials. Specific materials differ in the actual values of $V_{pI}$, $V_{Pll}$, $V_{max}$, and $\delta_{max}$. Typical values for metals, insulators and semiconductors, are shown in Table 1. Metals tend to have the lowest $\delta$ but only if they are atomically clean. The presence of oxides found on most metals significantly increases $\delta$. Insulators have higher $\delta$ than metals for the same $E_i$ and quite low values of $V_{pI}$. This makes them poor materials to have on the surface of a vidicon target.

<table>
<thead>
<tr>
<th></th>
<th>$\delta_{max}$</th>
<th>$V_{max}$</th>
<th>$V_{pI}$</th>
<th>$V_{Pll}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td>0.5-1.5</td>
<td>200-800V</td>
<td>100-300V</td>
<td>1000-3000V</td>
</tr>
<tr>
<td>Insulators</td>
<td>2-20</td>
<td>300-1500V</td>
<td>10-30V</td>
<td>1000-10000V</td>
</tr>
<tr>
<td>Semiconductors</td>
<td>1-3</td>
<td>100-500V</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 1: Typical range of secondary electron emission values$^{1,2,4}$ for atomically clean metals, insulators, and semiconductors.

Semiconductors have secondary emission characteristics that are between metals and insulators. The higher emission of insulators is related to their wider band gap. Electrons released within an insulator are less likely to lose energy by exciting other electrons across the band gap and more likely to reach the surface. Also a surface which is rough will have lower emission than a smooth surface of the same material. This is because a rough surface allows primaries to penetrate deeper and secondaries have more trouble escaping. The secondary emission characteristics of $a$-Se$^{(7,4)}$ and Sb$_2$S$_3$$^{(3)}$ a low emission coating used in vidicons is shown in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>$\delta_{max}$</th>
<th>$V_{max}$</th>
<th>$V_{pI}$</th>
<th>$V_{Pll}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$-Se</td>
<td>1.3</td>
<td>400V</td>
<td>40V</td>
<td>--</td>
</tr>
<tr>
<td>Sb$_2$S$_3$ (Solid)</td>
<td>1.15</td>
<td>500V</td>
<td>260V</td>
<td>1200V</td>
</tr>
</tbody>
</table>

Table 2: Secondary emission characteristics of $a$-Se$^{(7,4)}$ and Sb$_2$S$_3$$^{(3)}$ (Perpendicular Incidence)

The energy distribution of secondary electrons is shown in Figure 2 and has three distinct regions$^{8,9}$. The first region from 0–20 eV are true secondary electrons as opposed to reflected primaries. This region represents 90% of all emitted electrons when $E_p$>50 eV. In a vidicon, the low energy of these secondaries means they can easily be swept or moved by electric fields above the target surface. Region 2 are primary electrons that have been reflected some distance below the surface and have lost some energy before
escape. They represent about 7% of the total. Region 3 are primaries reflected at the surface with no energy loss and represent about 3% of the total. Secondary electrons are emitted at all angles with an $-\cos\theta$ dependence ($\theta$ measured from the normal). This dependence is relatively independent of other factors such as $E_r$ and the angle of incidence of the primary.

Secondary emission values are given for normal incidence ($\phi=0$). The value of $\delta$ ($E_r$ fixed) increases however, as $\phi$ is increased, and correspondingly, the value of $V_{pt}$ decreases. Published curves of $\delta$ versus $\phi$ for a-Se or Sb$_2$S$_3$ have not been found, but other materials show an increase in $\delta$ of about 10 to 40% when $\phi$ increases from 0 to 45°. $V_{pt}$ decreases by about the same amount. The increase in $\delta$ with $\phi$ tends to be small for rough surfaces.

In a vidicon, the readout process involves focusing an electron beam into a small spot on the target surface. The current components that flow at the surface of the target are shown in Figure 3. The beam current ($i_b$) has a distribution of electron energies which means that those electrons with enough energy will be accepted by the target ($i_a$) while those with insufficient energy are repelled ($i_{rep}$). The secondary electrons produced ($i_{sec}$) also have an energy distribution which depending on the electric field above the surface causes some of the electrons to be absorbed by the collector mesh ($i_{abs}$) while some return to the surface ($i_{ret}$). The net target current ($i_T$) is given by $i_T = i_{pra} - i_{sec} + i_{ret}$. Figure 4 shows $i_T$ as a function of $V_{S}$. It is derived from Figure 1 and shows stabilization points as well as charging direction indicated by arrows. The potential on the surface of an insulator ($V_2$) bombarded by an electron beam will become more negative if $\delta<1$ ($V_2<V_{p1}$) and more positive if $\delta>1$ ($V_2>V_{p1}$). This leads to each point on the surface having two possible equilibrium conditions\cite{10,11,12} known as cathode stabilization ($\delta<1$), and anode stabilization ($\delta>1$). Anode stabilization is replaced by second crossover stabilization if $V_C>V_{p1}$ but this is not generally the case in a vidicon. Cathode and anode stabilization will now be discussed.

B. CATHODE STABILIZATION (NORMAL VIDICON OPERATION)

For normal vidicon operation, we require the target surface potential $V_2<V_{p1}$ and therefore, $\delta<1$, and only negative charging occurs. Assuming vidicon cathode potential to be zero, the electron beam will charge the surface negatively until $V_2=0$, at which point beam electrons are repelled and negative charging ceases. This equilibrium condition is called cathode stabilization since the target surface is at the same potential as the cathode (See Figure 3).
Figure 3. Current components at the target surface and the two equilibrium conditions known as cathode and anode stabilization.

\[ i_T = i_{pri} - i_{sec} + i_{ret} \]
\[ i_T = 0 \quad \delta < 1 \]
\[ V_S = 0 \]
\[ i_T = 0 \quad \delta > 1 \]
\[ V_S = V_C \]

Figure 4. Target current \( (i_T) \) versus surface potential \( (V_S) \) showing stabilization points \( (i_T = 0) \). Arrows indicate charging direction.
When x-rays are absorbed in the \( \alpha \)-Se, photoconduction causes the surface potential to increase such that \( 0 < V_s \leq V_T \), where \( V_T \) is the target potential or substrate potential. Provided that \( V_s < V_{pf} \), the scanning electron beam will reestablish \( V_s = 0 \) as it passes over. The surface potential \( (V_s) \) will therefore continuously rise and fall at the frame rate of the camera (usually 30 frames/s).

In a vidicon camera with \( V_T < V_{pf} \) the condition \( V_s > V_{pf} \) can never be reached since under intense illumination (x-rays or light) \( V_s \) can be no higher than \( V_T \). This is the case for the typical 1" light sensitive vidicon for which \( V_T \) is 50V or less. In such a vidicon \( V_T < 1 \) and thus cathode stabilization is guaranteed. In a large area x-ray vidicon however, \( V_T \) can be greater than \( V_{pf} \) and the possibility of \( V_s > V_{pf} \) exists unless extra precautions are made.

C. ANODE STABILIZATION

If the surface potential of a vidicon target \( (V_s) \) exceeds \( V_{pf} \) then positive charging will occur. How high \( V_s \) will increase depends on the presence of other electrodes in the vidicon which collect the secondaries.

In any electron-optical system in which secondary electrons are produced the electrode to which the secondaries are attracted to and absorbed is called the collector. In a vidicon the collector takes the form of a mesh above the \( \alpha \)-Se surface. When secondary electrons are produced, their subsequent motion depends on the electric field between the surface and the collector grid. If the collector potential \( V_C \) is higher than \( V_s \) the secondaries are attracted away from the surface while if \( V_C < V_s \) the secondaries will return to the surface.

Referring to Figure 4 it can be seen that if \( V_C > V_s > V_{pf} \) then positive charging will occur and \( V_s \) will increase. This increase will continue until either \( V_s = V_{pf} \) or \( V_s = V_C \) which ever comes first. In a vidicon \( V_C \) is usually less than \( V_{pf} \) and therefore \( V_s = V_C \) will occur first. The condition \( V_s = V_C \) is called anode stabilization where the collector grid is the effective anode\(^{1.10} \). This position is stable since values of \( V_s \) above and below \( V_C \) correspond to negative and positive charging respectively. Figure 3 shows the relationship between \( i_{pr} \), \( i_{sec} \), \( i_{abr} \) and returned secondary current \( i_{rn} \) during anode stabilization. Should \( V_s > V_C \) occur, then \( i_{rn} \) will increase and the net current to the surface \( i_T = i_{pr} + i_{sec} + i_{rn} \) will increase to restore \( V_s = V_C \). Similarly if \( V_s < V_C \), \( i_{rn} \) decreases and \( V_s = V_C \) is restored. Anode stabilization is therefore the point at which secondary electron current absorbed by the collector is equal to the primary current and the net current for charging the surface is zero.
It is possible to operate a camera in the anode stabilized condition in which case it is called high velocity readout\textsuperscript{13,14,15,16,1,10}. Low velocity readout corresponds to cathode stabilization. High velocity readout is seldom used however, due to spurious shading signals caused by the redistribution of secondary electrons over the target. For our purposes anode stabilization is a condition which is to be avoided.

\section{Crossover and Its Prevention}

Crossover refers to the transition from cathode to anode stabilization\textsuperscript{17,18,19,20,21,12}. If a vidicon target has both anode and cathode stabilized regions, we find that the anode stabilized regions have a tendency to grow at the expense of the cathode stabilized regions until the entire target has crossed over to anode stabilization. This transition is a result of the large voltage gradient that occurs on the surface between the two regions. The large gradient causes pulling of the beam as well as secondary electrons toward the more positive anode stabilized region. This in turn robs the adjacent cathode stabilized region of electrons and causes its potential to rise. The crossover process is illustrated in Figure 5. Crossover can occur in a few seconds or may take minutes depending on the conditions. Crossover is accelerated by higher beam currents or illumination. The dynamics of crossover are complex since it depends on many factors in 3 dimensions. Factors which influence crossover are:

1) The secondary electron emission properties of the surface ($V_p$, $\delta_{max}$, $V_{max}$).
2) The beam current and its velocity distribution.
3) The angle of incidence of the electron beam to the collector mesh.
4) The illumination and its spatial distribution (image).
5) Beam bending and corresponding increases in $\delta$.
6) The velocity and angular distribution of secondaries.
7) The spatial redistribution of secondaries due to electric fields.
8) The capacitance of the target.

The growth of an anode stabilized region starting from a small spot is circular in the absence of illumination and is image dependant in the presence of illumination. Figure 6 is an image produced on an ordinary 1" light sensitive vidicon in which the target potential ($V_t$), nominally 50V, was raised to 200V. The anode stabilized region in this case is black since $V_e=V_c>V_t$ and the potential across the a-Se has reversed relative to cathode stabilization ($V_t=0$). A reversed potential on the a-Se reverses the photocurrent. In a large area vidicon, $V_t$ can be greater than $V_c$ in which case anode stabilization will appear white since the potential across the a-Se is reduced but not reversed.
Figure 5. Crossover from cathode to anode stabilization.

Figure 6. Crossover demonstrated on a 1" light sensitive vidicon. Target potential was raised from its normal value of 50V to 200V. Black region at top left is anode stabilized, while the rest of the image is cathode stabilized.
Crossover can be initiated by strong illumination which causes $V_s > V_p$, at some location. However, crossover is more often initiated at the edge of the area scanned by the beam. The surface potential on unscanned regions of the target is the same as the substrate ($V_s = V_p$). The higher the value of $V_p$, the more strongly the electron beam is attracted to the unscanned region and the higher the probability of crossover.

The angle of incidence of the electron beam to the collector mesh ($\theta_c$) can have a significant effect on target stability. While the value of $\delta$ for a given $E_i$ increases for non-perpendicular landing, this effect is only a minor problem. More important is the increase in landing energy $E_i$ for $\theta_c > 0$. To understand this, we must first realize that electrons, after passing through the collector mesh, are decelerated before reaching the target. The decelerating force acts only on the perpendicular component of velocity and not on the transverse. This is illustrated in Figure 7.

When an electron passes through the mesh at an angle $\theta_c$, its perpendicular ($E'_p$), transverse ($E'_t$), and total ($E'_t$) energies are given by:

\[ E'_p = eV_c \cos^2 \theta_c \]  (2)

\[ E'_t = eV_c \sin^2 \theta_c \]  (3)

\[ E'_t = eV_c \]  (4)

Upon reaching the surface at a potential $V_s$, the perpendicular energy $E_p$ has been reduced to:

\[ E_p = E'_p - e\left(V_c - V_s\right) = eV_s - eV_c \sin^2 \theta_c \]  (5)

The transverse energy at the surface ($E'_t$) is unchanged:

\[ E_t = E'_t = eV_c \sin^2 \theta_c \]  (6)
Figure 7. Non-perpendicular beam landing geometry.

1) Target After High Exposure

- $V_s > V_{pl} > V_{supp}$
- $i_{sec} > i_{pri}$
- $V_s$ very high
- Electric field returns all secondaries
- Negative charging

2) Recovering

- $V_s \sim V_{supp} < V_{pl}$
- $i_{sec} < i_{pri}$
- $V_s$ reduced to $V_{supp}$
- Negative charging continues

3) Recovered

- $V_s \sim 0$
- $i_{sec} \sim 0$
- $V_s$ close to zero

Figure 8. Recovery of cathode stabilization by the use of a suppressor mesh. Vidicon will be unconditionally stable if $V_{supp} < V_{pl}$. 
and the total electron energy at the surface \( E_i \) is:

\[
E_i = E_p + E_r = eV_s
\]  

(7)

The equilibrium condition where beam electrons are repelled is found by setting \( E_p = 0 \) in Equation 5 which gives:

\[
V_s = V_C \sin^2 \theta_C
\]  

(8)

(for cathode stabilization in dark)

Note that for perpendicular incidence \( (\theta_C = 0) \) the equilibrium surface potential in the dark is \( V_s = 0 \) as expected but if \( \theta_C \neq 0 \) then \( V_s \neq 0 \).

When the vidicon target is illuminated the surface potential \( (V_s) \) will rise a small amount \( \Delta V \). The surface potential will then be:

\[
V_s = V_C \sin^2 \theta_C + \Delta V
\]  

(9)

(when illuminated)

and the landing energy of the electrons \( E_i \) is thus:

\[
E_i = e\Delta V + eV_C \sin^2 \theta_C
\]  

(10)

The second term in Equation 10 is an extra landing energy above that which would usually occur for normal landing. In a vidicon, a typical value for \( V_C \) is 700V. If we assume \( \theta_C = 10^\circ \) then the extra landing energy is 21V. Considering that \( \Delta V \) is usually less than 2V the landing energy has increased substantially. To reduce secondary emission and prevent crossover it is therefore important to have the beam arrive at the mesh and surface as close to perpendicular as possible.

Various methods can be used to stabilize a vidicon against crossover. These can be divided into two categories, unconditionally stable and conditionally stable. Unconditionally stable means that either crossover cannot occur, or if it occurs, the vidicon will recover automatically. Conditional stability means that the vidicon can crossover and not recover but stabilizing methods makes this possibility unlikely. To avoid immediate crossover \( V_r \) should be increased slowly so that \( V_s < V_p \) at all times\(^{22} \). If \( V_r \) immediately assumes a large value \( (V_s = V_r > V_p) \) then \( \delta > 1 \) will occur and crossover results. Techniques for achieving stability will now be discussed.
E. LOW EMISSION COATINGS

The first crossover \( V_{pr} \) for an \( \alpha \)-Se surface is only about 40V (Table 2). Stability of the \( \alpha \)-Se target can be greatly improved by applying a thin coating of a material with a higher value of \( V_{pr} \). In the Saticon and other vidicons a layer of \( \text{Sb}_2\text{S}_3 \) is used for this purpose\(^{23,24,25,26,19} \). While a solid \( \text{Sb}_2\text{S}_3 \) layer can be used a porous layer is better. The \( \text{Sb}_2\text{S}_3 \) can be made porous by evaporating it in an argon atmosphere at \(-1 \) Torr pressure\(^{27,13} \). The pressure of the gas causes the \( \text{Sb}_2\text{S}_3 \) molecules to agglomerate in transit to the \( \alpha \)-Se surface. A thickness of 1000Å is typical. Porous \( \text{Sb}_2\text{S}_3 \) is also used in Chalnicon and Newvicon cameras\(^{28} \).

Any alternative to \( \text{Sb}_2\text{S}_3 \) must not only have low secondary emission it must also be capable of being applied without heating the \( \alpha \)-Se layer and it must not disrupt electron blocking action. Also it must have a high surface resistivity in order to avoid deterioration of the image. This excludes conductive coatings unless they are pixelated, that is, deposited as an array of small separate islands of material. Any metal coating must also maintain its low emission in the presence of air since it would be impractical to maintain an ultrahigh vacuum in the tube. A promising class of materials are the metallic blacks\(^{29,15} \). These are porous coatings made by evaporating metal in an inert gas atmosphere in the same manner as \( \text{Sb}_2\text{S}_3 \). Kawamura\(^{30,31} \) has used porous Ag to increase the crossover potential of an SEC camera to over 100V. Other materials such as Au, Ni, Zn and Bi are also known to form metallic blacks.

While \( \text{Sb}_2\text{S}_3 \) can provide unconditional stability for a 1" vidicon, \( (V_{pr}>50\text{V}) \), it cannot do so for the very large values of \( V_{y} \) in a large area vidicon. The ideal low emission coating for use in large area vidicons is one for which \( \delta<1 \) at all incident energies. Such a coating would provide unconditional stability. Few materials possess this quality. Two materials that have been reported with \( \delta<1 \) at all energies are carbon soot\(^{12,1,5,6,8} \) and nickel black\(^{1} \). However, these materials, have not been reported as a coating in a vidicon. Methods of applying these materials to \( \alpha \)-Se and possible pixelation would need to be developed.

F. THE SUPPRESSOR MESH

A possible means of making a vidicon stable against crossover is to introduce an additional mesh into the camera. By analogy, with other electron optic devices, this is called a suppressor mesh. This mesh is located between the existing field mesh and the target surface as shown in Figure 8. The suppressor mesh is held at a potential, \( V_{supp} \), just slightly less than the first crossover potential of the target, \( (V_{pr}) \). If the
target surface potential \( V_s \) should rise above \( V_{sup} \) (strong illumination), the electrical field between the surface and suppressor mesh will reverse and force all secondary electrons back to the surface regardless of whether \( \delta \geq 1 \) or \( \delta < 1 \). Therefore, negative charging occurs at all values of \( V_s \). A suppressor mesh vidicon with \( V_{sup} < V_p \) is therefore unconditionally stable against crossover. The suppressor mesh concept has been successfully used in non-vidicon cameras such as the C.P.S. Emitron\(^{33,1,18}\). (C.P.S.= cathode potential stabilized) and the SEC camera\(^{34,35,36,17,30,31}\) which have low values of \( V_p \) (<20eV). No previous reports of suppressor mesh vidicons have been found.

The original focus of the electron beam can be preserved by locating the suppressor mesh in such a position that the electric field above the target is undisturbed. In a vidicon the potential above the surface rises linearly from zero at the surface to \( V_F \) at the field mesh. The suppressor mesh is therefore placed in the plane corresponding to a potential of \( V_{sup} \). For example, a 1" vidicon may have a field mesh 3mm from the target surface with \( V_F = 300 \text{V} \). A suppressor mesh at \( V_{sup} = 70 \text{V} \) would therefore be placed at \( d_{sup} = 3 \times 70 \div 300 = 0.7 \text{mm} \). It is not essential that the original focus condition be preserved and the suppressor mesh may be placed at any distance that is in accordance with resolution and noise requirements. In this case focus is easily achieved by adjustment of the electron gun focus potential or focus coil current. If \( d_{sup} \) is too small, capacitance and noise will be high, the mesh may be in focus and the mesh may accidentally touch the target. If \( d_{sup} \) is too large for a given \( V_{sup} \) then resolution will deteriorate due to beam bending and space charge repulsion. The suppressor mesh absorbs ~50% of the beam current. This loss can be compensated in a large area vidicon by designing for a larger maximum beam current. (See Chapter 3)

It has been reported\(^{17}\) that the suppressor mesh in an SEC camera can cause a reduction in camera resolution. This is more related to the potential and spacing of the suppressor mesh rather than the mesh itself. In an SEC camera \( V_p \) is very low and the suppressor mesh is typically set at \( V_{sup} = 15 \text{V} \) and \( d_{sup} = 0.3 \text{ mm} \).\(^{34,36}\) According to McMullan\(^{36}\), the spacing of 0.3 mm is not entirely a satisfactory compromise. The electric field above the SEC target is about 150/0.3=50 V/mm. This is lower than the electric field above a vidicon target which is 100 to 300 V/mm (300 to 900V across 3 mm) and thus explains the reduced resolution. Boerio et al\(^{34}\) reports that SEC camera resolution increases to a point as \( V_{sup} \) increases and that a resolution of 1500 lines/in. is possible at \( V_{sup} = 30 \text{V} \) (conditionally stable). The conclusion is therefore, that a suppressor mesh need not deteriorate resolution as long as the electric field above the target surface is kept high (>100 V/mm).

The optimum suppressor mesh distance is a trade-off between noise and resolution and will depend on the
intended application. For a high resolution, high signal application, such as cardiac cine, the optimal $d_{\text{supp}}$ is smaller than for lower resolution, lower signal applications such as standard fluoroscopy. It is desirable when using a suppressor mesh that a low emission coating on the target should also be used. By increasing the value of $V_p$, then $V_{\text{supp}}$ may be increased and $d_{\text{supp}}$ may be maximized.

G. OTHER STABILIZING METHODS

In addition to low emission coatings and the suppressor mesh, other methods of improving stability exist. These could be used in conjunction with unconditionally stable methods or they could be used to produce a conditionally stable vidicon. While an unconditionally stable vidicon would be preferred to a conditionally stable one, it may turn out that a vidicon can be made in which the probability of crossover is sufficiently small so as to be acceptable, and has a simplified construction or superior performance compared to an unconditionally stable camera.

Three ways to improve stability are:

1) Keep surface potentials at the edge of the target low. The edge of the surface region scanned by the electron beam is a likely starting place for crossover. One can take special precautions to reduce the probability of crossover there. Two ways in which this can be done are shown in Figure 9. The first is to put a guard ring at the edge of the target. The ring is kept at a low potential and shields the beam from high potentials that are found beyond the scanned region. The second is to make the target electrode area under the photoconductor smaller than the scanned area. Since the unscanned area of the photoconductor does not have target electrode beneath it, the surface cannot rise up to $V_r$ due to dark current, light or x-rays. If the unscanned target area stays near zero volts, it cannot initiate crossover.

2) Ensuring perpendicular beam landing. This is particularly important near the edge of the target. Attention to the shape of the correction lens electrodes is needed to ensure that the lens works properly at its periphery. Dynamic correction methods are also possible.
Figure 9. Methods of improving the stability of the target.
3) Use a flood gun which has its cathode at \(-V_k=5\) V to 30 V (see Figure 9). Under normal operation, the flood gun electrons will be repelled by the target and not be noticed. However, if some part of the target surface should rise above 30 V, the flood gun will act to prevent any further rise\textsuperscript{37,38}. Since the flood gun is not focused like the scanning beam, much higher current densities can be obtained which improved the limiting action. In zoom mode the flood gun will also prevent unscanned regions of the target from developing large \(V_S\).

In a vidicon one or more of the above methods could be used for maximum stability. In the event that crossover does occur in a conditionally stable vidicon, it can be detected quite easily by monitoring the video signal. As an anode stabilized region grows, the edge of the region is characterized by positive charging which gives rise to a video signal of opposite polarity to normal video. When crossover is detected, the camera can automatically undergo a recovery procedure.

III. MATERIALS AND METHODS

A. 1" SUPPRESSOR MESH VIDICON

In order to test the suppressor mesh concept it was decided to first incorporate one into a conventional 1" \(a\)-Se vidicon. By modifying an existing design, we could quickly and easily investigate the suppressor mesh without worrying about the problems associated with designing a larger area vidicon. The vidicon modifications were done by an industrial collaborator\textsuperscript{39} and consist of adding a suppressor mesh and increasing the \(a\)-Se thickness from 5 \(\mu\)m to 20 \(\mu\)m. The target structure is then a 20 \(\mu\)m \(a\)-Se layer on a glass/ITO substrate with a thin (\(-0.2-0.5\) \(\mu\)m) porous Sb\(_2\)S\(_3\) layer on the \(a\)-Se free surface. The nominal operating potential on the target is then 200V with camera circuitry modified to allow up to 1000V. A diagram of the 1" suppressor mesh vidicon is shown in Figure 10 and a photograph is shown in Figure 11. A metal pin was inserted into the glass face plate to make a connection to the target electrode. This design has three advantages. First, it leaves the metal ring available for connection to the suppressor mesh. Since the suppressor mesh needs to be close to the \(a\)-Se layer, it is easier to mechanically fix it to the faceplate than to the electron gun assembly.
Figure 10. The 1" suppressor mesh vidicon.

Figure 11. Photograph of the 1" suppressor mesh vidicon.
Second, it allows the area of the target electrode to be smaller than the scanned area which aids in stability and, third, it reduces the stray capacitance of the target which helps to keep amplifier noise low. The tube is magnetically scanned and magnetically focused. The faceplate is made of glass so that the tube can be tested with light as well as with x-rays. The suppressor mesh and field mesh are 0.5 mm and 3 mm from the target respectively. The suppressor mesh has 1000 holes per inch while the field mesh is 750 holes per inch both with a transparency of ~50%.

The useful imaging area of the tube is a circular region 0.8" in diameter. The vidicon was tested for stability against crossover with different values of $V_{\text{supp}}$ and $V_r$. To induce crossover a spot of light ~5 mm in diameter was projected onto the center of the target. The brightness of the spot was varied and the level necessary to induce crossover was recorded. The effect of beam current, illumination and $V_{\text{supp}}$ on the growth of anode stabilized regions was investigated. Also the $\delta$ versus $V_s$ curve for the target surface was measured. This was done by temporarily suspending beam current and illuminating the target to set $V_s=V_r$. $V_r$ was set to a fixed value and then the beam was re-enabled. The signal current created on the first scan was measured for both $V_{\text{supp}}=0$V and $V_{\text{supp}}>500$V. When $V_{\text{supp}}=0$V the measured signal corresponds to the beam current which lands since secondaries return to the surface. When $V_{\text{supp}}>500$V, the measured signal is equal to the beam current minus secondary electrons which leave the surface. The value of $\delta$ can be determined using Equation 1 and is given by:

$$\delta = \frac{i_s(V_{\text{supp}}=0V) - i_s(V_{\text{supp}}=500V)}{i_s(V_{\text{supp}}=0V)}$$

(11)

B. 6" SUPPRESSOR MESH VIDICON

As a further test of the effectiveness of the suppressor mesh, one was incorporated into a 6" demountable x-ray vidicon. The a-Se target of the vidicon has a 4" diameter imaging area with a thickness of 150 μm. The nominal target potential ($V_T$) is 1500V although potentials up to 5000V can be accommodated. The target to suppressor mesh distance ($d_{\text{supp}}$) and target to field mesh distance ($d_F$) are ~2.5 mm and 15 mm respectively. The pitch of the field mesh and the suppressor mesh are 333 lines per inch. The tube has a short electrostatic focus and short magnetic deflection. (See Chapter 3) To provide perpendicular beam landing a collimator lens is formed between the field mesh and the drift cylinder. The focal length of the lens is controlled by the ratio of field mesh potential ($V_F$) and drift potential ($V_D$). $V_F$ and $V_D$ are adjustable from zero to +3000V while $V_{\text{supp}}$ is adjustable from 0 to 150V.
Three different target surfaces were tested: 1) a-Se with no added coating; 2) a solid Sb$_2$S$_3$ layer, and; 3) a porous Sb$_2$S$_3$ layer. Both the solid and porous Sb$_2$S$_3$ were evaporated from a quartz crucible and wire basket combination. The 99.999% pure Sb$_2$S$_3$ powder from ESPI (Electronic Space Products Inc.) was pre-melted before evaporation to avoid splattering. The solid layer was evaporated at a pressure of ~10^{-6} Torr to a thickness of 1000Å and was orange in colour. The porous layer was evaporated with an argon pressure of 0.3 Torr and colour varied between light brown, dark brown, and green. During evaporation the argon pressure is maintained with both the pump and gas inlets valved off. This was found necessary to prevent gas turbulence from disrupting the evaporation process. In this high pressure evaporation the Sb$_2$S$_3$ appears as a cloud above the crucible which engulfs the target. The standard piezoelectric thickness monitor in the evaporator was not reached by this cloud. Porous layer thickness was therefore estimated by microscopic examination. Stability of the large area suppressor vidicon was evaluated with the three target surfaces. The effect of collimator lens adjustment on stability was also investigated.

IV. RESULTS AND DISCUSSION

A. 1" SUPPRESSOR MESH VIDICON

The vidicon was first tested with $V_{supp}=70$V. Since 1" non-suppressor mesh vidicons crossover at about $V_f=75$, then $V_{supp}=70$V should provide unconditional stability. The vidicon did indeed display unconditional stability for $V_f$ up to 800V. This limit was not one of instability but rather a limit due to excessive dark current and white spots. At the nominal value of $V_f=200$V the x-ray sensitivity was about 3 times higher than in a non-suppressor vidicon (limited to $V_f=50$V) with the same 20 μm a-Se layer (see Figure 12). The shape of the signal versus target potential curve shown in Figure 12 is characteristic of a-Se and is discussed further in Chapters 6 and 7 (See Chapter 6, Figure 6 and Chapter 7, Equation 1). No signs of mesh beat or microphonics were apparent and resolution was not significantly degraded when compared to a non-suppressor mesh vidicon.

When $V_{supp}$ was increased above 100V, anode stabilization would grow slowly inward from the edges. In the absence of illumination the growth can take many minutes to fill the target. A precise value of $V_{supp}$ for which crossover at the edge begins is difficult to measure since near threshold the anode stabilized region can nucleate at a random time and position at the edge of the target and its subsequent growth is slow. The critical value of $V_{supp}$ is about 90V.
Figure 12. Signal current versus $V_T$ for the 1" suppressor mesh vidicon with x-ray illumination. A light sensitive (non-suppressor mesh) vidicon is normally operated at $V_T = 50V$.

Figure 13. Signal level required at the target center for crossover of the 1" suppressor mesh vidicon versus $V_{supp}$. 
Assuming that nucleation of anode stabilization at the edge could be prevented, the target would be conditionally stable for $V_{\text{supp}} > 90V$. The degree of stability in this mode was assessed by increasing the intensity of a 3 mm light spot at the center of the target until crossover occurred. Figure 13 shows the signal level required for crossover versus $V_{\text{supp}}$. The signal level required for crossover at the center is about 70% of the beam current and is independent of $V_{\text{supp}}$ for $V_{\text{supp}} > 100V$. This indicates that if edge nucleation could be eliminated a high degree of conditional stability could be achieved with large $V_{\text{supp}}$ or no suppressor mesh at all. Signal levels greater than 70% of the beam current would have to be avoided. The degree of stability at the center for $V_{\text{supp}} = 100V$ was also measured at different values of $V_r$. The signal level required to cause crossover was found to be independent of $V_r$. This was to be expected since crossover is dependent on surface potential and not the potential across the $\alpha$-Se.

A curve of $\delta$ versus $V_s$ for the 1" suppressor vidicon is shown in Figure 14. For comparison the secondary emission curve for Sb$_2$S$_3$ as given by Dobretsov and Gomoyunov is also shown. The two curves agree closely for $V_s > 400V$ but diverge somewhat below 400V. The difference is probably due to the exact nature of the surface including contamination and absorbed gases. Surface effects are less pronounced at higher values of $V_s$ since secondaries are emitted from deeper within the material. The value of $V_p$ from the curve is 140V which is about 50V higher than the critical value of $V_{\text{supp}}$. Part of this difference can be explained by the energy distribution of emitted secondary electrons which is about 20 to 30 eV wide. For most secondaries to be returned to the surface, $V_s$ will need to be 20 to 30V more positive than $V_{\text{supp}}$. Unconditional stability therefore requires that $V_{\text{supp}}$ be about 20 to 30 eV less than $V_p$. Another factor that reduces the critical value of $V_{\text{supp}}$ is beam bending. When crossover is imminent $V_s - V_{\text{supp}}$ and the electric field above the surface is weak. The beam may then bend toward regions of high illumination and the non-perpendicular landing increases $\delta$ or lowers the effective value of $V_p$.

The ability of the suppressor mesh to return secondary electrons to the target surface is shown in Figure 15. The current collected by the target ($i_t$) is shown as a function of $V_s$ when $V_{\text{supp}} = 20V$ and $V_{\text{supp}} = 520V$. For $V_{\text{supp}} = 520V$ the curve displays the standard beam acceptance shape. The fast initial rise is due to the electron beam energy spread while the subsequent fall is due to secondary emission lost from the surface. When $V_{\text{supp}} = 20V$ the curve is the same until $V_s = 20V$ is reached. Above $V_s = 20V$ the electric field above the surface is reversed and secondary electrons begin to return to the surface. For $V_s >> 20V$ the current saturates at the value of the beam current.
Figure 14. Curve of $\delta$ versus $V_s$ for the 1" suppressor mesh vidicon. Curve for Sb$_2$S$_3$ by Dobretsov and Gomutunara also shown for comparison. The value of $\delta$ was derived using Equation 11.

Figure 15. Curve of signal current versus surface potential ($V_s$) with $V_{sup}=20$V and $V_{sup}=520$V.
The rate of growth of crossover was difficult to quantify since it depends on many factors including $V_{supp}$, illumination level, beam current, size and shape of crossover region and position of crossover region on the target. Some qualitative observations concerning crossover are:

1) The rate of crossover is strongly dependant on illumination. In the dark, complete target crossover may take minutes while strong illumination can reduce crossover time to seconds.

2) The rate of crossover depends on $V_{supp}$. For $V_{supp} < -90$V anode stabilized regions shrink, while values of $V_{supp} > -90$V anode stabilized regions grow. A value of $V_{supp}$ can always be found for which an anode stabilized region is stationary.

3) Crossover becomes more rapid as beam current is increased.

4) A value of $V_{supp}$ near 90V may be found such that small induced anode stabilized regions shrink and disappear whereas large induced regions persist.

B. 6" SUPPRESSOR MESH VIDICON

The first large targets tested were a 150 μm Xerox plate with the polymer surface coating intact and a 300 μm α-Se plate with no surface coating. These targets crossed over very easily. The value of $V_{supp}$ necessary to maintain stability ($V_{supp} < 30$V) was so low that resolution was greatly affected.

Next, a solid Sb$_2$S$_3$ layer was added which improved stability. Observations concerning the stability of the solid Sb$_2$S$_3$ layer are:

1) The critical value of $V_{supp}$ was about 45V.

2) When illuminated at $V_{supp} < 45$V, anode stabilization would grow inward a short distance and stop. When illumination was removed the anode stabilization ring would recede. The inward extent of the crossover could be minimized by proper adjustment of the collimator lens and by keeping $V_{supp}$ low but could not be totally eliminated.

3) X-ray images could be obtained with $V_T > 1500$V and about 80% of the central target area cathode stabilized. An example image is shown in Figure 16.

4) When illuminated with $V_{supp} > 45$V, anode stabilization would grow inward from the edges but did not recede when illumination was removed.

5) Anode stabilized regions appeared black when $V_T < V_{supp}$ and white when $V_T > V_{supp}$ as expected.

6) Resolution deteriorated rapidly if $V_{supp}$ was reduced below 30V.
Figure 16. X-ray image of a human hand phantom obtained with the 6" demountable x-ray vidicon with suppressor mesh and solid Sb$_2$S$_3$ layer. Stability was achieved in the center area only. \( (V_f = 1500\text{V}, V_{supp} = 30\text{V}) \)

Figure 17. Signal level required for crossover at the center and edge of the target versus collimator lens adjustment for the 6" demountable vidicon and solid Sb$_2$S$_3$ layer.
The effect of collimator lens adjustment is shown in Figure 17. The collimator lens is used to produce perpendicular beam landing as described in Chapter 3. The strength of the collimator lens is controlled by the ratio of the field electrode potential \( (V_F) \) to the drift electrode potential \( (V_D) \). The signal level required in a small spot to cause crossover is plotted as a function of \( V_F \) \( (V_D \) fixed) for spots located at the center and near the edge. Stability at the center of the target was relatively independent of \( V_F \) while stability at the edge was optimum when \( V_F/V_D = 5 \) \( (V_F=2500V, V_D=500V) \). This ratio was also confirmed at \( V_D=400V, V_F=2000V \). Observation of the live image while adjusting \( V_F \) confirmed \( V_F/V_D = 5 \) to be the condition of perpendicular landing at the edge. For \( V_F/V_D > 5 \) the image displays "porthole" that is the edges of the image are lost when the electron beam curves inward. Overall the solid Sb\(_2\)S\(_3\) layer was useable but did not provide unconditional stability over the whole surface as desired. The apparent low value of \( V_F \) for this layer may have been due to the surface contamination by the backstreaming of pump oil but this was not confirmed.

A porous Sb\(_2\)S\(_3\) layer was then applied over the solid Sb\(_2\)S\(_3\) layer. Due to difficulties in controlling evaporation the actual thickness of the layer (>20 \( \mu \)m) was larger than intended. When tested in the vidicon it was found to greatly improve stability. Stable operation was achieved for values of \( V_F \) up to 3000V and \( V_{supp} \) up to 150V with no ring of anode stabilization at the edge. An example image is shown in Figure 18. The excessive thickness was found to be detrimental to resolution and produced negative after images not present in the solid Sb\(_2\)S\(_3\) tests. These negative after images are believed to be caused by trapping and a larger than normal potential across the thick Sb\(_2\)S\(_3\) layer. During x-ray illumination there is an increase in potential across the Sb\(_2\)S\(_3\) layer which results in a decrease in potential across the \( \alpha \)-Se layer and a corresponding loss in sensitivity. When the x-ray illumination at a given region on the target is reduced the potential across the Sb\(_2\)S\(_3\) decreases and the potential across the \( \alpha \)-Se increases. During the time that these potentials are changing (delayed by trapping effects), however, the \( \alpha \)-Se has a potential across it which is lower than its equilibrium value. The lower sensitivity of this region with respect to its surroundings results in a negative after image. The thickness of the porous Sb\(_2\)S\(_3\) was reduced quite easily by brushing off the excess with a small paintbrush leaving some of the porous Sb\(_2\)S\(_3\) still adhering to the solid Sb\(_2\)S\(_3\). Resolution and low lag were restored while maintaining good stability.

An unexpected observation was the appearance of the suppressor mesh in the image for \( V_{supp} > 120V \). In retrospect it was realized that this would occur if \( V_{supp} \) is increased without increasing \( d_{supp} \). Since resolution for \( V_{supp} > 100V \) does not increase significantly, larger values of \( V_{supp} \) are not warranted at the given \( d_{supp} \). In future, larger values of \( d_{supp} \) could be used, which would decrease capacitance. No microphonic effects were observed.
Figure 18. X-ray image of a human vertebra obtained with the 6" demountable x-ray vidicon with suppressor mesh and porous Sb$_2$S$_3$ layer. Stability was achieved at the center as well as the edges. ($V_g = 1000V$, $V_{app} = 100V$).
V. CONCLUSIONS

The suppressor mesh was first tested in a 1" $\alpha$-Se vidicon and provided cathode stabilized operation for target potentials exceeding 800V. The larger target potentials used provided greater x-ray sensitivity than is possible without a suppressor mesh. The suppressor mesh also proved successful in providing unconditionally stable operation in a 6" demountable x-ray vidicon with target voltages in excess of 3000V. A porous Sb$_2$S$_3$ layer, provided that this layer is kept thin, was found necessary so that $V_{\text{supp}}>50$V could be used for good resolution. The suppressor mesh and porous Sb$_2$S$_3$ combination should therefore provide stable operation for future large area x-ray vidicons.
REFERENCES


CHAPTER 5

FABRICATION AND CHARACTERIZATION OF AN
AMORPHOUS SELENIUM LAYER FOR A LARGE AREA
X-RAY SENSITIVE VIDICON

I. INTRODUCTION

A large area x-ray sensitive vidicon is a vacuum tube device which uses a photoconductive x-ray sensor and is read out in real time using a scanning electron beam. The photoconductor we are using for this application is amorphous selenium (a-Se). Although other x-ray photoconductors could be used, a-Se gives the best trade-off at this time in terms of x-ray absorption, sensitivity, low dark current, and ease of manufacture in large areas without defects. a-Se has been highly developed as the x-ray photoconductor in an x-ray imaging system known as Xeroradiography. Xeroradiography is a toner based read-out system which uses an a-Se layer coated on an aluminum substrate. In operation the a-Se plate is given a positive surface charge. Due to the extremely low dark current of the a-Se plate, the positive surface charge can be held for hours. It was hoped that these highly developed x-ray sensitive plates could be used directly in the x-ray vidicon. This unfortunately is not possible since xeroradiographic plates when charged negatively by an electron beam exhibit a much higher dark current, defects, and non-uniformities, and are not usable in the x-ray vidicon. The asymmetry in the electrical properties of the xeroradiographic plate is due to differences in electrical blocking action at the two a-Se interfaces. Our goal is to change the structure and or process by which the xeroradiographic plate is made such that it will accept a negative charge and thus be usable in an x-ray sensitive vidicon. This must be done in such a way so as not to sacrifice desirable properties such as x-ray sensitivity and efficient carrier transport characteristics of a typical plate designed for positive charging.

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* This chapter will form the basis of a paper to be submitted to Medical Physics on the theoretical and practical aspects of using an a-Se layer as the target of a large area x-ray vidicon.
II. BACKGROUND

A. DARK CURRENT REQUIREMENTS FOR A LARGE AREA VIDICON TARGET

Sensitivity (ie the number of nA/cm$^2$/R/s) in $\alpha$-Se$^3$ increases with electric field. Similarly, the amount of dark current also increases with the electric field used. The maximum sensitivity of an $\alpha$-Se layer thus depends on how large an electric field can be sustained without unacceptably high dark current. In theory one should be able to simply subtract any dark current from the measured signal to obtain the true x-ray signal. For small uniform dark currents this is reasonable. As the electric field in $\alpha$-Se increases, however, large spatial non-uniformities show up in the form of small spots of high dark current known as white spots$^{4,5,6,7}$. Not only does the dark current become spatially very non-uniform, it also becomes temporally non-uniform. Some white spots which occur at high electric fields blink$^{4,7}$ on and off with a frequency $\sim 0.2$ to 1 Hz. Some increase in dark current can also occur as a result of x-ray exposure. This effect, known as fatigue$^8$, can cause dark current after-images to appear. The electric field in $\alpha$-Se must therefore be limited to a value where dark current is either negligible or uniform enough to be subtracted as a constant.

Another problem associated with high dark current is shot noise. For a vidicon, (large or small), dark current shot noise $i_{na}$ will be the dominant electronic noise source if it exceeds amplifier noise $i_{na}$. This will occur if $i_{na} = [2eI_dB]^{1/2} > i_{na}$ where $I_d$ is the dark current and $B$ is the bandwidth. There is, therefore, an upper limit on $I_d$ to have negligible dark current shot noise.

In a 1" light sensitive $\alpha$-Se vidicon (Saticon) a dark current of $\sim 0.2$ nA/cm$^2$ is typical$^9$. For a circular image area of 2 cm in diameter the total dark current is $\sim 0.6$ nA. This current is less than the electronic noise (1 to 2 nA rms, 5 MHz) in these tubes and therefore spatial and temporal non-uniformities in the dark current and dark current shot noise are negligible. This low level of dark current in the Saticon is possible due to the effective blocking layers that exist at the two $\alpha$-Se interfaces.

For a 9" diameter vidicon (410 cm$^2$, $i_{na} \sim 2-4$ nA rms in 5 MHz) to have negligible dark current shot noise the dark current will need to be less than 2500 nA ($[2(1.6\times10^{-19}C)(2500\text{ nA})(5\text{ MHz})]^{1/2} = 2$ nA) or 6.1 nA/cm$^2$. 


Another consideration for dark current is that its spatial variation $\Delta I_d$ from pixel to pixel should be less than amplifier noise ($-2$-$4$ nA rms in $5$ MHz) which as a dark current density on the $a$-Se plate is $\Delta I_d < 0.005$ nA/cm$^2$.

High dark currents can limit the range of signal currents to the preamplifier. The range of signal current is the difference between beam current ($-1000$ nA) and the dark current level. In a $1''$ Sb$_2$S$_3$ vidicon a dark current of $30$ nA is considered acceptable. In a $9''$ vidicon this would represent a dark current per unit area of $I_d < 0.07$ nA/cm$^2$.

The dark current of a xeroradiographic plate can be computed from its potential decay per unit time. To do this the plate is first charged with positive ions by means of a corotron. A non-contacting electrostatic voltmeter is then used to monitor the surface potential. May and Lubinsky$^{10}$ report that a $300$ $\mu$m $a$-Se plate charged to $+3000$V ($10^7$ V/m) decays $40$ to $100$ V in $20$ minutes. Assuming the worst case of $100$V, the dark current is $0.0015$ nA/cm$^2$ ($I/C = dV/dt, C = 18.5$ pF/cm$^2$). They also report the dark current to be uniform so that the variation in dark current is $<< 0.0015$ nA/cm$^2$. Positively charged $a$-Se plates therefore easily meet the dark current requirements of a large area x-ray vidicon. Note that the dark current per unit area of a xeroradiographic plate is $\sim 1/100$ that of a Saticon target. No reports have been found of plates exhibiting low dark decay for negative surface potential and suitable for x-ray use. It should be possible, however, by appropriate control of blocking layers to produce an $a$-Se plate which has a dark current for negative charging that is as low as a typical $a$-Se plate is for positive charging. Producing such a plate is the focus of this chapter.

B. BLOCKING CONTACTS

When an $a$-Se layer is charged (either Xerox plate or vidicon target) we would like the surface charge and corresponding image charge in the substrate to be dissipated only by the action of x-rays on the plate. X-rays produce electron hole pairs in the bulk which travel under the influence of the electric field toward the surface charges. The electrons cancel positive charge at one surface while the holes cancel negative charge at the other surface. Unfortunately, some dissipation of charge does occur in the dark. There are three sources of dark current$^{2,8}$. These are:

1) Injection of carriers from the substrate into the bulk.
2) Injection of carriers from the surface into the bulk.
3) Thermal generation of carriers in the bulk.
The magnitude of dark current sources 1) and 2) depends on charge polarity, but source 3) is polarity independent. Injection of carriers from the surface is prevented by construction of blocking contacts. A blocking contact\textsuperscript{11,12} is a configuration in which carriers are prevented from moving into the bulk to which they are attracted by electric forces. A contact which allows some injection of carriers is called "injecting" while a contact that allows carriers to move freely is called "ohmic". With ohmic contacts on a semiconductor the \(I-V\) characteristics of the device will depend only on the properties of the bulk material. If one or more of the contacts are non-ohmic, then the \(I-V\) characteristics depend on the contacts as well as the bulk. To say that a contact is blocking one must also state the conditions under which it is blocking\textsuperscript{12}. That is a contact may be blocking under one polarity but not for the opposite. Also a contact may be blocking for low applied potentials but not for higher potentials. For a vidicon target we wish the contacts to be blocking when the free surface is negative and the substrate positive and to as high a potential as possible, typically \(10^7\) to \(10^8\) V/m. For each of the three dark current sources there are one or more physical processes responsible. Table 1 gives the various processes that can occur at different locations in the photoconductor and for different barrier types.

<table>
<thead>
<tr>
<th>Barrier Type</th>
<th>Location</th>
<th>Processes</th>
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<td>- Barrier lowering</td>
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<td>- Tunnelling</td>
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<td>Insulating Barrier</td>
<td>Substrate</td>
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<td>Bulk Thermal Ionization</td>
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<td>- Frenkel-Poole effect (field assisted thermal generation)</td>
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</table>

Table 1. Dark current processes

These barrier types and processes will now be discussed.

1) \textbf{The Schottky Barrier}

If a semiconductor comes in direct contact with the metal of a substrate a Schottky barrier\textsuperscript{13,14,15,16,17,18,19,8} will be formed. The formation of a Schottky barrier is shown in Figure 1. The metal and semiconductor
Figure 1. Schottky barrier formation. See text for explanation of terms.

Figure 2. The Schottky barrier under an applied field. The electron barrier in this case is larger than the hole barrier making the preferred polarity of the semiconductor surface positive.
are shown separated (Figure 1a) with electron energy bands measured relative to the vacuum level. For the metal the potential from the Fermi level to the vacuum level is called the work function $\Phi_m$. The semiconductor has a similar work function $\Phi_s$ measured from its Fermi level to the vacuum. The Fermi level is the energy at which the probability of an electron occupying a state at that energy (if the state exists) is one half. The conduction band is located below the vacuum level by $\chi_e$ which is called the electron affinity and the valence band is located below the conduction band by $E_g$ which is called the band gap. In a semiconductor the valence band is almost 100% occupied by electrons with any missing electrons referred to as holes. Holes which move in the valence band carry positive charge. The conduction band in a semiconductor on the other hand, is almost empty, however, those electrons which are present are free to move under the influence of an electric field. When the metal and semiconductor are brought together (Figure 1b), electrons move from the metal to the semiconductor or vice versa so as to equalize the Fermi levels. Space charge in the semiconductor is responsible for bending of the valence and conduction band and shifting of the Fermi level. Another effect which occurs as a result of the union is image charge lowering of the barrier in the semiconductor. Whenever a charge comes close to a metal it is attracted to charges of opposite sign which are induced in the metal surface. This image charge results in a lower potential for charges in the semiconductor near a metal than there would otherwise be.

The effect of biasing a Schottky barrier for the two different polarities is shown in Figure 2. For our example we have chosen the case where $\Phi_m - \chi_e > E_g/2$. When the metal is biased negative with respect to the semiconductor (Figure 2a) the electrons in the metal see a relatively high barrier and the metal-semiconductor contact is said to be blocking for electrons. If the potential is raised high enough however, the barrier will be lowered enough to permit injection. If we bias the metal positively (Figure 2b) we find that the barrier to holes going into the valence band is small and hole injection occurs at relatively low potentials. Therefore, in this example the contact is said to be injecting for holes but blocking for electrons up to a given potential.

The flow of carriers through a Schottky barrier can occur due to carriers which pass over the barrier (thermionic emission) or due to carriers which tunnel through it (field emission). For tunnelling to occur the barrier must be narrow. The width of the barrier depends on the semiconductor equilibrium carrier concentration which in turn depends on the position of the Fermi level relative to the valence and conduction bands. For a wide band gap, intrinsic semiconductor the barrier width is large and Schottky barrier tunnelling is negligible, which closely describes the situation for $a$-Se.
Current density over a Schottky barrier due to thermionic emission is given by:

\[ J = AT^2 \exp\left(\frac{-e\Phi_B}{KT}\right) \exp\left[\frac{1}{KT} \left(\frac{E_p e^3}{\varepsilon_\sigma \varepsilon_r}\right)^{\frac{1}{2}}\right] \]  

(1)

Where:

- \( J \) = current density
- \( A \) = Richardson constant (120 A/[cm²K²])
- \( T \) = temperature (300K)
- \( e \) = elementary charge (1.6x10⁻¹⁹C)
- \( \Phi_B \) = barrier potential (e.g. \( \Phi_M - \chi_S \))
- \( K \) = Boltzmann constant (1.38x10⁻²³J/K)
- \( E_p \) = Photoconductor electric field
- \( \varepsilon_\sigma \) = permittivity of free space (8.85x10⁻¹² F/m)
- \( \varepsilon_r \) = photoconductor relative permittivity (\( \alpha\text{-Se} \varepsilon_r=6.3) \)

Previously it was shown that a dark current of less than 0.0015 nA/cm² would be desirable. The barrier height needed to achieve this dark current can be calculated using Equation 1. For an \( \alpha\text{-Se} \) photoconductor with an internal field of 10⁷ V/m the required barrier height for 0.0015 nA/cm² is 1.18 eV.

Using the theory of Schottky barriers one should be able to engineer an appropriate blocking contact by choosing a metal with a value of \( \Phi_m \) to produce the desired blocking with \( \alpha\text{-Se} \) (\( \Phi_e=4.72 \text{ eV}, \chi_e=3.5 \text{ eV}, E_g=2.5 \text{ eV})^{24} \). This approach has been shown to hold for a limited number of semiconductors and metals but fails to work for the majority of materials\(^{18,19} \). One reason for this is metal-semiconductor chemical reactions that produce an intermediate compound. \( \alpha\text{-Se} \) is known to be chemically reactive with most metals\(^{7,2,8} \). Another explanation proposed by Bardeen\(^{25} \) is that a large density of surface states on the semiconductor can effectively "pin" the Fermi level\(^{17,18,19} \) of the semiconductor to the Fermi level of the metal regardless of \( \Phi_m, \Phi_r, \chi_e \) and \( E_g \). These surface states could be due to structural defects or contamination. Fermi level pinning is illustrated in Figure 3. When the materials are brought together, the Fermi levels equalize by charge flow between the metal and the surface states. Since the required charge flow is satisfied by the surface states, no charge is required from the semiconductor bulk and thus no band bending occurs. Another consequence is that the barrier height produced is independent of the metal used. This does not mean that blocking contacts cannot be made when surface states are present, it just means that barriers are less easily engineered. An empirical rule\(^{31,18,19} \) that holds for many covalent materials (\( \alpha\text{-Se} \) is covalent) is that surface states tend to be concentrated below the bottom of the conduction band at a depth of \( 2/3 E_g \). Applying this rule to \( \alpha\text{-Se} \) the electron barrier at a metal (substrate)
Figure 3. Fermi level pinning.

Figure 4. The insulating barrier.
interface would be 1.6 eV while the hole barrier would be 0.83 eV. This may account for the low dark current observed in \(a\)-Se layers with the surface charged positive and the substrate negative.

2) **Insulating Barrier**

Another method of creating a blocking layer is to introduce a thin insulating barrier\(^8,16,26\) between the metal and the semiconductor as shown in Figure 4. The most common insulator used with \(a\)-Se is \(\text{Al}_2\text{O}_3\), although organic polymers are also sometimes used. An insulator is characterized by having a large \(E_g\) and few volume generated carriers\(^14\). Since the barrier to electrons and holes is very large, charge transport does not occur by normal conduction in the conduction or valence band. Charge transport instead occurs as the result of either tunnelling or breakdown.

If the insulating layer is sufficiently thin, (<200 Å) electrons in the metal can effectively “tunnel” through the barrier as opposed to having to surmount it. The equations that govern tunnelling are complex and different equations apply to different ranges of applied potential\(^27,14\). For low applied potentials (<0.1 V) tunnelling current is ohmic (proportional to applied potential) but is exponentially related to insulator thickness and barrier height. For larger potentials the tunnelling current is exponentially related to applied potential, insulator thickness, and barrier height. Tunnelling barriers are difficult to control due to their sensitivity to thickness and insulator preparation. If the insulator is too thin, the tunnelling probability will be high and not act as a barrier. If the insulator is too thick, the tunnelling probability will be low and insulator breakdown will occur before appreciable tunnelling occurs.

Insulating barriers can be characterized by their breakdown strength (electric field that can be sustained before breakdown conduction occurs\(^28,29,26\). The breakdown process is complex and not well understood. The two main competing theories are avalanche impact ionization and field emission (tunnelling) from internal flaws. Avalanche breakdown occurs when electrons or holes in the insulator have enough energy to ionize further carriers. A cascade of these ionizations can occur resulting in a substantial flow of current. Also field emission or tunnelling can cause internal flaws or impurity states to ionize. Actual breakdown in insulators may be due to both mechanisms. A characteristic of breakdown is an abrupt increase in current when a critical breakdown field is reached. Typical breakdown fields for insulators are \(10^8\) to \(2\times10^9\) V/m. The breakdown strength of \(\text{Al}_2\text{O}_3\) for layers less than 200 Å is \(\sim1.2\times10^9\) V/m\(^30,28\). If currents are low enough to prevent Joule heating then breakdown in usually non-destructive. If the insulator is too thick, breakdown can become erratic both in time as well as position.
When a potential is initially applied to the $a$-Se layer with insulator blocking contact (see Figure 4a) the voltage across the insulator will be small and given by:

$$V_I = \frac{V_T}{1 + \frac{\varepsilon_{a-Se} d_{a-Se}}{\varepsilon_{Al_2O_3} d_{Al_2O_3}}}$$

Where:
- $V_I$ = potential across insulator
- $V_T$ = total potential across $a$-Se and insulator
- $\varepsilon_{a-Se}$ = $a$-Se relative dielectric constant (6.3)
- $\varepsilon_{Al_2O_3}$ = insulator relative dielectric constant
- $d_{a-Se}$ = $a$-Se thickness
- $d_{Al_2O_3}$ = insulator thickness

For a 500 $\mu$m thick $a$-Se layer with 100 $\AA$ thick $Al_2O_3$ ($\varepsilon_r=8$) insulating barrier and 5000V applied potential we find $V_I=0.08V$. This is well below the breakdown potential for this thickness (12V).

After the initial charging, currents will flow in the $a$-Se due either to x-ray absorption or dark current (bulk or surface). Charge will develop across the insulator which in turn increases the potential across it. At some point the insulator will conduct either by tunnelling or breakdown. In equilibrium the insulator current will match the $a$-Se current. Charge at the insulator/$a$-Se interface will be of opposite polarity to that in the substrate. (Figure 4b) The key to blocking action by an insulating barrier is that current in the insulator is only that needed to cancel excess interface charge. In other words, no carriers originating from the substrate should inject into the $a$-Se and pass through to the surface. Insulator conduction should therefore be due to carriers travelling toward the substrate or else the recombination probability at the insulator/$a$-Se interface should be high (traps).

Insulating barriers will be discussed further, when details of the Xerox 125 $a$-Se plate are considered.

3) **Unipolar Conduction Barrier**

An ideal blocking contact is one in which one type of carrier flows freely while the other does not. This can be accomplished by introducing an appropriate material between the substrate and $a$-Se layer such that a barrier is formed for one type of carrier but not the other. Figure 5 shows an example of an interfacial layer used when the substrate is to be biased positive. Electrons in the $a$-Se can flow freely to the substrate while holes in the substrate have a large barrier to the $a$-Se valence band. This type of barrier
Figure 5. Unipolar conduction barrier. The wide bandgap semiconductor shown at the interface makes a blocking contact for holes but not electrons.

Figure 6. Surface trap barrier.
is used in the a-Se vidicon (Saticon) in the form of an n-type CeO₂ layer formed between the ITO (Indium Tin Oxide) substrate and the a-Se layer.

To be an effective blocking layer for holes, the interface material (substrate positive) should have its conduction band \( (E_C) \) at the same level or lower than the conduction band of the a-Se and its valence band \( (E_V) \) should be lower than that of the a-Se. Since a-Se has \( E_g = -2.2 \) eV and its Fermi level \( (E_F) \) is approximately midway in the band gap, the blocking layer should have \( E_C - E_F \leq 1.1 \) eV and \( E_F - E_V > 1.1 \) eV. CeO₂ has \( E_C - E_F = 0.8 \) eV and \( E_F - E_V = 2.6 \) eV \( (E_g = 3.4 \) eV\) which makes it nearly ideal. Similarly, a different wide bandgap material could be chosen to provide electron blocking if required.

The CeO₂ unipolar conduction barrier will be discussed further when details of the Saticon are considered.

4) **Surface Trap Barrier**

Another method of forming an effective blocking contact is by having traps either at the a-Se free surface or at the a-Se/substrate interface. These traps hold externally applied charge and prevent it from traversing the a-Se layer. The traps can be contained in a thin layer of the a-Se itself or alternatively an extra trap layer may be used.

A trap is an energy state in the forbidden band caused by a structural imperfection or impurity. States located above the Fermi level are normally empty and are therefore electron traps while states below the Fermi level are normally full and so are hole traps. A band diagram of a-Se with surface traps is shown in Figure 6. Note that the presence of surface states does not cause a depletion region at the a-Se surface as it does in doped semiconductors. This is because the a-Se is nearly intrinsic and has few bulk carriers to deplete.

When a potential is applied across the a-Se layer, charge is held in the surface traps as shown in Figure 6. Electron traps are filled at the negative surface and hole traps are filled at the positive surface. Charge trapped at the surface can become thermally released which leads to dark current. The probability of release depends on the depth of the trap. The depth of an electron trap is its distance (energy difference) from the conduction band while the depth of a hole trap is its distance from the valence band. For low dark current the trap release probability must be low, which requires deep surface traps. By arranging one surface to have electron traps and the other surface hole traps the electrical characteristics of the layer can be made asymmetric.
Traps can also be used to assist the blocking action of a pre-existing Schottky, Insulating, or Unipolar conducting barrier. The space charge of filled traps causes bending of the conduction and valence bands next to the pre-existing barrier thereby changing its conductivity. One should avoid having both electron and hole traps at the same pre-existing barrier. While filling of one trap type strengthens blocking, filling of the other will weaken blocking. This effect may be responsible for fatigue\textsuperscript{24} or increased dark current after exposure of the \(a\)-Se to light or x-rays. When initially charged the negative surface has only trapped electrons while the positive surface has only trapped holes. After exposure both electrons and holes become trapped at each surface, resulting in a cancellation of each others space charge. This weakens blocking and dark current increases.

The trap barrier provides the sole blocking action at the free surface of an \(a\)-Se plate since there are no metals, insulators or unipolar semiconductors present. These traps are also responsible for the negligible lateral conductivity of the surface essential for image retention. The degree of blocking action caused by traps at the \(a\)-Se/substrate interface, however, is unclear at this time.

In the Saticon a layer of \(\text{Sb}_2\text{S}_3\) is used on the free surface of the \(a\)-Se as an electron trapping material while LiF is used near the substrate as a hole trapping impurity.

5) **Bulk Processes**

High resistivity photoconductors such as \(a\)-Se are referred to as depleted semiconductors since when initially charged any carriers in the valence band or conduction band are swept out. Bulk originated dark currents can occur either when electron hole pairs are thermally ionized across the band gap or when a single electron or hole is thermally ionized from a defect\textsuperscript{34,16}. Thermal ionization of a free electron hole pair in \(a\)-Se is unlikely because of the relatively large band gap (~2.2 eV). This leaves the thermal ionization of defects which has been shown to be the dominant bulk dark discharge effect in \(a\)-Se\textsuperscript{35,36}. Figure 7 shows dark current originating from the ionization of neutral defects and from the ionization of a charged defect. In both cases a net space charge is left in the previously neutral bulk.

Amorphous selenium consists of chains of doubly bonded selenium. Structural defects in \(a\)-Se are predominantly singly bonded, negatively charged selenium atoms (Se\textsuperscript{−}) and corresponding triply bonded, positively charge selenium atoms (Se\textsuperscript{+}). These are called valence alternation pairs (VAP)\textsuperscript{35,36}. In pure \(a\)-Se, Se\textsuperscript{−} and Se\textsuperscript{+} defects occur in equal numbers. If impurities such as halogens or alkalis are added to the \(a\)-Se the balance will be disrupted. Halogens, by stealing electrons, increase the number of Se\textsuperscript{+}
Figure 7. Dark current originating from the bulk.

Figure 8. Frenkel-Poole effect.
electron traps while alkalis increase the number of Se\textsuperscript{−} hole traps. These traps or defects are deep (near the center of the forbidden band) and trapping time is on the order of seconds or minutes.

While the bulk as a whole is charge neutral, the defects themselves are charged. The thermal ionization of these defects can therefore be electrically assisted by the Frenkel-Poole effect\textsuperscript{22,23}. The Frenkel-Poole effect is the bulk equivalent of Schottky barrier lowering where an electric field in the \textit{a}-Se helps to lower the Coulombic barrier at a charge defect as shown in Figure 8. An extension of the Frenkel-Poole theory by Onsager can also be used to describe field assisted thermal ionization\textsuperscript{16}. The Frenkel-Poole effect only applies to defects that are charged when unoccupied (such as Se\textsubscript{3}\textsuperscript{+} and Se\textsubscript{5}\textsuperscript{−}). Dark decay by defect ionization has been shown to occur in \textit{a}-Se layers doped with Cl, Te, I, K and other impurities. The process is believed to also occur in pure \textit{a}-Se, but is small and difficult to separate from surface injection effects. The surface potential decay of an \textit{a}-Se plate by defect ionization is called xerographic depletion discharge (XDD)\textsuperscript{34,35,37,38,39}. The XDD process is shown in Figure 9 for a Cl doped \textit{a}-Se layer that is charged positively. Initially charges are held at the surface and substrate. In time, defects become ionized, leaving a free hole and Se\textsubscript{5}\textsuperscript{−} defect. The unpaired Se\textsubscript{5}\textsuperscript{−} therefore, gives rise to an immobile negative space charge. The free holes cancel negative charge in the substrate and the surface potential decreases. At some point called the depletion time, (\(t_d\)) all of the charge in the substrate will be neutralized and positive surface charge will be coupled to the uniform negative space charge in the bulk. After \(t_d\), ionized free holes recombine with the negative space charge, instead of charges in the substrate and the decay process is much slower. This change in dark decay rate is evidence for the XDD process and bulk ionization of defects.

A large area x-ray vidicon \textit{a}-Se photoconductor should contain as few deep defects as possible. If the defect concentration can be kept small, then the ionization of the defects will eventually saturate (also known as deep depletion)\textsuperscript{37}. Once saturation occurs, dark current originating in the bulk will be low. The requirement for low bulk dark current is more stringent in a large area vidicon than in a Saticon because of the larger volume of \textit{a}-Se. Fortunately \textit{a}-Se plates designed for x-ray use have carefully controlled impurity concentrations designed to keep deep trap concentrations low\textsuperscript{35}.

C. THE XEROX 125 PLATE

By far the most common xeroradiographic plates used are the \textit{a}-Se plates of the Xerox 125 system\textsuperscript{5,40}. These 9.5 x 14 inch plates consist of a 150 \(\mu\)m thick layer of \textit{a}-Se coated onto a 2 mm thick aluminum
Figure 9. Dark decay due to xeroradiographic depletion discharge in a Cl doped a-Se layer.

Figure 10. Typical dark decay curve for an a-Se plate (from Schaffert).
substrate. The ultrapure selenium is alloyed with nominally 0.35% (35,000 ppm) As and -12 ppm Cl. The exact compositions used is a trade secret. The As is added to prevent crystallization of the a-Se and increase the electron lifetime while the Cl is added to compensate for the deleterious effects of As on hole lifetime. The amount of Cl added is adjusted so that the a-Se is ambipolar (has a significant electron and hole range) and also to maximize both the electron and hole range so that they are greater than the a-Se thickness. Too much Cl will annihilate the electron range while too little will result in poor hole range. Since x-rays are absorbed in the bulk, both carriers are needed to prevent space charge build up and maximize sensitivity. The Al substrate is polished and preoxidized to produce a very uniform Al₂O₃ layer of 15 to 100Å thickness. The a-Se is deposited by thermal evaporation with the substrate held at a precise temperature of in the range of 70-95°C. The evaporation boat is heated to ~270°C and an evaporation rate of ~2-4 µm/min is used. Exact details are not in the public domain. After evaporation, a thin polymer (~2000Å) layer is added to help blocking and make the surface durable (a-Se is very easily scratched). In Xeroradiography, the free surface of the plate is charged positively with ions from a device known as a corotron (or scorotron) to a potential of ~1500V. The corotron produces these ions using a high voltage corona discharge in the air above the plate. The plate is then placed in a portable light tight cassette. Inside this cassette the a-Se can retain a useful charge for over one hour. X-rays absorbed in the a-Se release electron hole pairs which reduce the surface charge to create a charge image. Readout of the image involves toner in a manner similar to that in a photocopier.

Dark current characteristics of a-Se plates are usually measured by charging the surface with a corotron and monitoring the surface potential in time with a non-contacting electrostatic voltmeter. This produces the xerographic decay curve. The first feature of the curve is a maximum potential to which it can be charged. This is called the acceptance potential. This acceptance potential is different for positive and negative charging. For a Xerox 125 plate, positive acceptance potential is ~1500V while negative acceptance potential is less than 300V. Typical decay curves for a positively and negatively charged Xerox plate are shown in Figure 10. For positive charging, there is an initial fast discharge followed by a much slower decay. Dark decay measurements can be divided into two types: rested dark decay and fatigued dark decay. Rested dark decay is the dark decay after several hours of resting the uncharged plate in the dark which empties traps. Fatigue is an increase in dark decay caused by previous exposure to light or x-rays and is caused by trapping near a barrier.

1) **Details of the Free Surface**

The free surface of the xeroradiographic a-Se plate retains charge on its surface via surface states or traps.
These surface states can be due to unsatisfied surface (dangling) bonds or surface impurities. The high light sensitivity of these plates implies that the traps must be located in a thin layer at the surface <100Å thick\textsuperscript{31}. A newly evaporated \textit{a-Se} plate shows high dark decay which is minimized by aging or surface treatment\textsuperscript{8,33}.

Fractionation occurs during the evaporation of \textit{a-Se} producing an As rich surface\textsuperscript{43,36}. The degree of fractionation depends on the \textit{a-Se} boat temperature, evaporation rate and whether evaporation is done to completion. Leiga\textsuperscript{5} reports that Xerox 125 plates may have a surface As concentration up to 10\%. It is known that As in \textit{a-Se} causes hole traps\textsuperscript{2,41}. This would aid in the retention of a positive surface charge. Fender and Zanrossa have shown that increasing surface As concentration increases the acceptance potential of xeroradiographic plates\textsuperscript{44}. Too much surface As, however, can lead to a rippling of the \textit{a-Se} surface called reticulation\textsuperscript{5,44}. Trubisky and Neyhart\textsuperscript{45} have also shown that a significant reduction in surface injection occurs as the result of oxidation of surface As.

By treating the \textit{a-Se} surface with different liquids or gases, the dark current can be modified\textsuperscript{8}. Treatments which reduce dark current for positive charging and increase dark current for negative charging are called donor substances, since they easily donate an electron to leave a positive charge. Donor substances include Nigrosine\textsuperscript{31,33}, Isopropanol, and NH\textsubscript{4}OH. Treatments which increase dark current for positive charging and decrease dark current for negative charging are called acceptor substances. Examples of acceptor substances are FeCl\textsubscript{3}, ozone, and Chloranil.

The free surface is coated with a polymer 0.05-0.02 μm thick\textsuperscript{46}. From the Xerox patent literature, the polymer used on the Xerox 125 is probably a mixture of polyester (Mylar), polyurethane (Vithane) and polyvinylidene chloride (Saran)\textsuperscript{46}. The polymer is added to improve wear resistance and protect the surface from environmental contamination which could increase dark current. In some applications the polymer may be omitted\textsuperscript{47}.

\section*{2) Details of the Substrate Interface}

Although many different substrate materials have been reported to provide good blocking contacts to \textit{a-Se}, the most common, and that used by the Xerox 125 plate, is an oxidized Al substrate with an oxide thickness between 15 to 100 Å. Plates using oxidized Al are superior in terms of uniformity and freedom from defects. Al\textsubscript{2}O\textsubscript{3} also helps to make the \textit{a-Se} more adhesive. The Xerox 125 plate oxide layer is grown by glow discharge\textsuperscript{5}. Other oxidation methods such as anodization and thermal oxidation are also
possible. For the same oxide thickness, the acceptance potential and dark current may vary with oxidization method. If Al₂O₃ is reduced below 15Å, dark decay increases slowly while Al₂O₃ thicknesses above 100Å exhibit a significant increase in residual potential. This high residual cannot be due to a potential across the Al₂O₃ itself, since the residual potential exceeds the breakdown potential of the oxide (12V for 100Å). The Al₂O₃ must therefore have some influence on bulk deep traps which have been shown to cause residual potential. It seems likely, therefore, that traps play a major role in substrate blocking as they do in surface blocking.

While tunnelling most likely occurs in the Al₂O₃ layer it is unlikely that this tunnelling provides insulator blocking action. Zhang and Champness have measured the resistance of Al₂O₃ films similar to those used for xeroradiographic a-Se plates. They find the resistance of Al₂O₃ films 50 to 100Å thick are less than 10⁷Ω-cm². This is too low to provide blocking action. They also report that thinner oxide films can provide higher acceptance potentials and lower dark current than thicker oxides. If not an insulating barrier then blocking must be due to a Schottky barrier or trap barrier. Schaffert has shown that the dark decay of surface potential in a-Se plates cannot be explained by Schottky barrier action alone².

While the nature of substrate blocking is still unknown, some possible mechanisms might be:

1) The Al₂O₃ supplies oxygen to the a-Se. Oxygen is known to create electron traps.
2) Fractionation of chlorine compounds occur at the beginning of the evaporation. Selenium chlorides have lower melting points than pure selenium. Chlorine like oxygen creates electron traps.
3) The Al₂O₃ prevents a chemical reaction from occurring between the Al and a-Se which is detrimental to blocking.
4) The Al₂O₃ prevents crystallization of the a-Se since the Al₂O₃ is amorphous and the Al is crystalline. Crystalites have been seen by some researchers at the Al₂O₃/a-Se interface.
5) The higher thermal conductivity of Al and Al₂O₃ over a-Se causes the a-Se condensing on the substrate to see a lower temperature than a-Se condensing in the bulk. a-Se which freezes quickly as it lands will have more structural defects or traps.

Many experiments have been made involving the introduction of an intermediate layer other than Al₂O₃. Some of the substances tried have been Se (crystalline), SeO₂, ZnS, MgF₂, As, As₂O₃, Te, Ge, As₂S₃, CdO, Al₂Se₃, polystyrene, lucite, S, and GaSe₃. Most substances unfortunately have no
effect or else increase dark current for one or both polarities. In cases where dark decay for negative charging is lowered (As$_2$S$_3$, lucite, S) the decay is still worse than it is for positive charging. The substrate interface appears to always be more electron blocking than hole blocking regardless of any interface substance used.

3) **Separation of Dark Current Components in a Xerox 125 Plate**

Determining the relative contributions of surface injection, substrate injection, and bulk dark current to total dark current in an a-Se plate is difficult. This difficulty arises from the fact that we cannot monitor currents in the layer without significantly disrupting the layer itself. We must, therefore, rely on indirect measurements.

A property of the Xerox 125 plate and most other xeroradiographic a-Se plates is that the acceptance potential for positive charging is significantly higher than the acceptance potential for negative charging (Figure 10). *This fact alone tells us that the high dark current exhibited by a negatively charged plate can only be due to surface or substrate injection and is not a bulk effect.* Which source of injection (surface or substrate) is dominant has not been determined. Therefore, efforts to modify a xeroradiographic plate for negative charging must concentrate on the a-Se interfaces, rather than the bulk.

With respect to a positively charged plate, Schein$^{46}$ has been able to separate bulk and interface components by measuring plates of different thicknesses at constant electric field. The interface contribution is determined by extrapolating to a plate of zero thickness. Similar to Xerox 125 plates, his plates show an initial fast discharge, followed by a much slower discharge. Plates measured 10 seconds after charging (initial fast decay period) to a field of 10$^7$ V/m have a bulk dominated dark current that increases with a-Se thickness. For a 300 µm a-Se layer, the bulk contribution 10 seconds after charging is about 7 times larger than the interface contribution. After the initial fast discharge (~1 minute) the dark current reduces to a value that is consistent with the interface contribution. The fast initial discharge is therefore most likely due to ionization of bulk defects which subsequently becomes saturated (deep depletion).

A large area vidicon with good blocking contacts for negative charging will therefore probably also exhibit an initially high dark current lasting a few minutes followed by a lower interface limited dark current.
D. THE SATICON AND HARPICON

In addition to Xeroradiography, a-Se is also used in light sensitive television cameras called the Saticon\(^7,8,9\) and the Harpicon\(^59,60,61,62\). These tubes are usually 2/3" or 1" in diameter with an a-Se layer 2 to 8 \(\mu\)m in thickness. The Harpicon differs from the Saticon in that it uses a higher target potential and achieves gain in the target through avalanche multiplication. The structure of a Saticon target is shown in Figure 11. The ITO (Indium Tin Oxide) serves as a transparent conductive electrode from which the signal is taken. A thin layer of CeO\(_2\) helps reduce defects by inhibiting crystallization and also helps in providing some blocking action. The bulk of the layer is a-Se doped with \(-2\%\) As to prevent crystallization. A thin layer containing as small percentage of Te is added when an increased red sensitivity is required. Finally the top layer or free surface is made of Sb\(_2\)S\(_3\). This layer serves three purposes. First, it prevents direct injection of the electron beam into the a-Se which would result in a high dark current\(^7\). Secondly, it provides a blocking contact to the a-Se for negative surface charge. And thirdly, Sb\(_2\)S\(_3\) has a relatively low secondary emission as compared to a-Se. This allows higher target voltages to be used without fear of image crossover (see Chapter 4). The Sb\(_2\)S\(_3\) layer is also sometimes made porous which helps to further reduce secondary emission. Improvements in the Saticon structure such as the Saticon II and Saticon III have been made but the basic structure is still the same as the original Saticon\(^9\).

The a-Se requirements of a Saticon are in some respects less stringent than those of a xeroradiographic plate. Since the Saticon layer is only 5 \(\mu\)m thick, as compared to >150 \(\mu\)m for xeroradiographic plates, the range of carriers need not be as great. Also since light is absorbed in a thin layer of a-Se adjacent to the ITO substrate, the transport in the a-Se is only by holes which travel toward the more negative free surface. Although only hole transport participates in image formation that does not mean that electron transport can be ignored. Poor electron transport can result in a space charge build up of dark current electrons. Space charge disrupts the normal electric field distribution in the target resulting in fatigue and after images. Typical dark current\(^9\) for a Saticon at 10\(^7\) V/m is 0.2 nA/cm\(^2\). This is much higher than a xeroradiographic plate at the same electric field (0.002 nA/cm\(^2\)) but yet poses no practical problem with regard to Saticon operation. This is because the Saticon image is read out at 30 fps whereas the xeroradiographic image may be held for tens of minutes before readout. Similar to the acceptance potential of a xeroradiographic plate the Saticon shows a sharp increase in dark current if a threshold target electric field is exceeded. In the Saticon this is typically in the range of 1-5 x 10\(^7\) V/m\(^6\). Some of the excess dark current is localized as white spots which appear randomly on the target and in increasing numbers
Figure 11. Structure of the Saticon target.

Figure 12. Band diagram of the Saticon target with a negative surface charge.
as the electric field is increased.

The generally accepted band diagram for a Saticon target\(^7\) is shown in Figure 12. ITO is an n-type semiconductor which is highly conductive due to a high level of structural defects\(^6\). Its Fermi level is therefore, close to its conduction band and therefore has a band diagram similar to a metal. CeO\(_2\) is a wide band gap (3.4 eV) n-type semiconductor. The \(\alpha\)-Se has a band gap of \(-2.2\) eV and a Fermi level which is near the centre of the gap. Taken together the ITO/CeO\(_2/\alpha\)-Se interface forms a unipolar conducting barrier which allows easy conduction of electrons and is blocking for holes (ITO is biased positively in a Saticon). The Sb\(_2\)S\(_3\) which has a band gap of 1.7 eV is slightly p-type and has poor electron conduction (electron trapping), which acts as an effective electron blocking layer. Since the Sb\(_2\)S\(_3\) is thin compared with device resolution it does not matter whether the electrons are trapped in the Sb\(_2\)S\(_3\) bulk or at the actual \(\alpha\)-Se/Sb\(_2\)S\(_3\) barrier.

A Harpicon is basically a Saticon which has been improved to allow electric fields in the \(\alpha\)-Se up to \(2 \times 10^8\) V/m without excessive dark current. At fields of \(-1 \times 10^8\) V/m, avalanche multiplication occurs in the \(\alpha\)-Se allowing gain in the target of 10 to 100 times. This increased gain is essential for producing HDTV (High Definition Television) cameras with high sensitivity to allow large depth of field. A large depth of field (ability to focus sharply on both near and far objects simultaneously) requires the aperture of the camera, and thus the amount of light used for imaging, to be reduced. To achieve this high gain, changes in the \(\alpha\)-Se target were required. In the Harpicon, the \(\alpha\)-Se adjacent to the CeO\(_2\) layer is doped with LiF. The LiF is said to reduce the electric field at the interface by producing positive space charge (trap aided blocking). As a consequence, the LiF layer significantly reduces the number of white blemishes seen in the image for electric fields on the order of \(1 \times 10^8\) V/m. Most likely other process and structural differences have been incorporated in the Harpicon to allow operation at high electric fields but these methods are not public knowledge. X-ray sensitive Harpicons have been reported\(^6\) which are over 10 times more sensitive than an equivalent x-ray Saticon. These 2/3" diameter devices have an 8 \(\mu\)m \(\alpha\)-Se layer and a Be window. The tubes were tested with characteristic radiation of Cr, Cu and Mo (5.4, 8.0, and 17.4 keV respectively). A graph of signal current versus target voltage for an x-ray Harpicon as well as a light sensitive Harpicon is shown in Figure 13. From the graph it can be seen that the light sensitive Harpicon shows a saturation in signal current before the onset of avalanche is reached. The x-ray Harpicon, on the other hand, shows a gain that increases approximately linearly up to the point of avalanche. A greatly increased signal for x-rays is therefore possible by improvement of blocking layers. The possibility of using electric fields \(>10^7\) V/m to increase sensitivity in a large area x-ray vidicon is discussed further in Chapter 7.
Figure 13. X-ray and light characteristics of the Harpicon target. The light sensitive Harpicon curve was adapted from Tanioka et al. while the x-ray Harpicon curve was adapted from Maruyama et al. Note that for electric fields less than 80 V/μm the light sensitive Harpicon shows saturation while the x-ray Harpicon does not.

Figure 14. Layout of a-Se plate used to test additional CeO$_2$ and Sb$_2$S$_3$ blocking layers.
The use of CeO₂, LiF, and Sb₂S₃ can probably be incorporated into the structure of a xeroradiographic plate to produce a large area vidicon target with suitably low dark current when the free surface is negatively charged.

**E. LARGE AREA X-RAY VIDICON TARGET DESIGN**

The requirements of a large area x-ray vidicon target incorporate qualities found in both the xeroradiographic plate and the light sensitive Saticon tube. From the xeroradiographic plate we desire the large area and large a-Se thickness which give it good x-ray absorption and signal generating properties. Large thicknesses are possible since xeroradiographic grade a-Se has a large range for both electrons and holes. The low dark current per unit area found in a xeroradiographic plate is also desirable, since the x-ray vidicon has a much larger area, and low dark current per unit area keeps the total dark current low. Since trap density in the bulk is considerably reduced if the substrate is heated⁶⁶⁶⁷, it is therefore preferred that a large area vidicon a-Se layer should be made with a heated substrate in order to reduce trapping and bulk dark decay. Qualities of the xeroradiographic plate which are not required is its ability to charge well in the positive polarity and its protective polymer surface layer which makes the plate rugged enough for use with a toner readout system.

Qualities of the Saticon target which are required are its ability to be charged with an electron beam. This means two things. First the a-Se must have appropriate blocking action for its free surface to be charged negatively without excessive dark current. And second, a layer such as the Sb₂S₃ is needed to prevent direct electron injection into the a-Se and to keep secondary emission low. Another desirable property of the Saticon target is its ability to produce images at the rate of 30 fps with very little photoconductive lag (<3%). This requires that the a-Se have few deep traps in its bulk. Although rapid readout is not a requirement of a xeroradiographic plate it should however be capable of it since we know, from its low residual potential, that it also has few deep traps in its bulk. In a Saticon, blocking and light sensitivity are both critical to the condition of the a-Se adjacent to the ITO. Compromises between good blocking a good light sensitivity are made. For an x-ray target however blocking contacts can be developed without concern as to light sensitivity.

Four different approaches we have considered for making the target are:

1) Keep the method of producing the xeroradiographic type a-Se layer the same but introduce additional layers at each surface for blocking. Specifically, use a layer of CeO₂
next to the substrate and a layer of $\text{Sb}_2\text{S}_3$ on the surface as is done in the Saticon but use the same $a$-Se and $a$-Se evaporation process used for xeroradiographic plates.

2) Use a conventional xeroradiographic plate with all its good qualities as a positive plate and invert the structure to make a negative plate. That is deposit a conductor on the free surface, bond a new substrate to this conductor then remove by chemical means the old substrate/conductor. This method hinges on the assumption that the blocking action is inherent to the surfaces of the $a$-Se itself and that the position of these surfaces with respect to the substrate and free surface will be reversed in order.

3) Change the process by which the xeroradiographic $a$-Se is deposited to make it have good negative properties. Specifically use an unheated substrate during the $a$-Se evaporation which according to Schaffert provides the desired effect\(^2\) (see Figure 10).

4) Introduce impurities into the $a$-Se at the beginning and end of the evaporation\(^6\). Impurities such as LiF and As at the beginning of the evaporation should provide hole traps near the substrate while impurities such as O and Cl at the end of the evaporation should provide electron traps at the surface.

Thus far we have been able to try approaches 1, 2, and 3. Approach 4, however, requires the use of equipment for co-evaporation of $a$-Se and impurities and will need to wait until such facilities become available to me.

III. MATERIALS AND METHODS

Three separate types of targets were constructed and tested for use in a large area vidicon.

A. TARGET WITH ADDITIONAL $\text{CeO}_2$ AND $\text{Sb}_2\text{S}_3$ BLOCKING LAYERS

Two $a$-Se plates were made using additional $\text{Sb}_2\text{S}_3$ and $\text{CeO}_2$ layers. The two plates differed in the type of ITO substrate used. Plate 1 was 1.1 mm thick glass with an ITO resistivity of 10 $\Omega/\square$ (Applied Energy Technologies). Plate 2 was 2 mm thick glass with an ITO resistivity of 1000 $\Omega/\square$ (Balzers). Both plates were divided into quadrants. Figure 14 shows the construction of the experimental $a$-Se plate. By testing the four combinations of $\text{CeO}_2$ and $\text{Sb}_2\text{S}_3$ one should be able to determine whether negative blocking action is occurring and whether one or both layers is required.
CeO$_2$ was evaporated onto two adjacent quadrants of the ITO substrates using electron beam evaporation of CeO$_2$ pellets (3-6 mm pieces) from a graphite crucible. A thickness of 200 Å was used to match that used in Saticons. The CeO$_2$ was 99.9% pure from Cerac. After evaporation the CeO$_2$ layer was a uniform translucent yellow. 300 µm of xeroradiographic grade $\alpha$-Se was then evaporated onto all quadrants of both substrates using standard $\alpha$-Se thermal evaporation with the substrate heated to ~70°. Finally a solid Sb$_2$S$_3$ layer 1000Å thick was evaporated onto two adjacent quadrants of the $\alpha$-Se surfaces by thermal evaporation. The plate was rotated 90° between evaporation of the CeO$_2$ and Sb$_2$S$_3$ resulting in the four desired combinations of upper and lower blocking contacts. The Sb$_2$S$_3$ is 99.999% pure 300 mesh powder from Electronic Space Products Incorporated (ESPI). It was found necessary to pre-melt the Sb$_2$S$_3$ powder into a solid slug before use in the evaporator. The Sb$_2$S$_3$ was evaporated from a 1 cm diameter quartz crucible in a tungsten basket (R.D. Mathis Limited).

The finished plates were tested for charge acceptance and dark current for both positive and negative corotron charging. Charging was done by passing the plates under the corotron by means of a motorized stage. The plate was passed under the corotron 8 times with each pass separated by ~15 seconds. This was done to put the plate into deep depletion so that the measured dark decay would be more caracteristic of a vidicon target which is continuously charged. A potential of 5000V was used on the corotron wire, with the corotron positioned 3 mm above the $\alpha$-Se surface. The plate was kept in the dark throughout the process. With this potential and position the corotron was capable of charging a Mylar sheet to +/- 1800V. Potential on the charged plate was monitored using an electrostatic surface potential probe (Monroe Electronics Meter Model No. 144S-4, Probe No. 1009B) placed 2 mm above the surface (probe hole diameter 1 mm). Discharge of the plates was monitored for 20 minutes following charging. Decay curves for positive and negative charging of each quadrant on both plates were obtained.

**B. INVERTED TARGET**

If one assumes that the blocking action in a xeroradiographic plate takes place in thin layers at the upper and lower surfaces of the $\alpha$-Se then one should be able to make a negative plate by moving the conductive substrate to the opposite $\alpha$-Se surface. To test this hypothesis an inverted target was constructed as follows. A Xerox 125 $\alpha$-Se plate (150 µm) was cut into a 4.6" diameter circle. Positive and negative discharge curves were measured on this plate as described earlier. A layer of Indium 4000 Å thick was then evaporated on the $\alpha$-Se surface. The thin polymer layer on the Xerox 125 plate was retained. Indium
was chosen for its low melting point to avoid heating the \( \alpha \)-Se which could have initiated crystallization. It was found that heating of the \( \alpha \)-Se occurs from both condensing metal on its surface and radiant heat from the evaporation source. The \( \alpha \)-Se plate was shielded as much as possible from radiative heat and the substrate was in contact with Al heat sink. Positive and negative decay curves were measured again by corotron charging the indium in the same manner as one would a free \( \alpha \)-Se surface. A circular glass substrate 2 mm thick was then bonded to the indium surface with Varian Torrseal vacuum epoxy. The old Al substrate was then dissolved in hydrochloric acid (37\% HCl diluted with an equal part H\(_2\)O). It was found that the heat produced during the Al etching was enough to raise the temperature above 40°C which damaged the plate. A heat exchanger consisting of 10 turns of 1/4" Cu tubing wound 6 inches in diameter was added to the acid bath. By passing cold water through the Cu coil the HCl bath was kept below 20°C during the entire etch. When the last Al dissolved the plate was immediately removed and rinsed in distilled water. Examination of the plate revealed that the free surface was Al\(_2\)O\(_3\) which etches more slowly than Al in HCl. Both the positive and negative decay curves were again measured by corotron charging of the new free surface. A thin solid 1000Å Sb\(_2\)S\(_3\) layer was then added to the inverted target in the same manner described previously, and the decay curves remeasured. The steps involved in making the inverted target are shown in Figure 15.

The completed inverted target was then placed in the 6” demountable vidicon for testing. Tests of dark current versus target voltage were performed.

C. **UNHEATED SUBSTRATE TARGET**

Schaffert\(^2\) has shown that by not heating the substrate of a xeroradiographic plate, positive charging is degraded while negative charging is greatly improved (See Figure 10). The reason for this phenomenon has not been established, but it is possibly related to the formation of a thin \( \alpha \)-Se layer adjacent to the substrate which is different from the bulk and provides the appropriate blocking action. To verify Schaffert’s results and to produce a negative charging plate for the vidicon an unheated substrate plate was made and tested.

Two \( \alpha \)-Se layers on ITO substrates were made. The first plate was made conventionally using a heated substrate (~70°C) and served as the control. The second plate was made in the same manner except that the substrate was unheated. Both plates had a \( \alpha \)-Se thickness of 300 \( \mu \)m. Positive and negative decay curves were measured for these two plates.
Figure 15. Construction of the inverted a-Se target.
IV. RESULTS AND DISCUSSION

A. TARGET WITH ADDITIONAL CeO$_2$ AND Sb$_2$S$_3$ BLOCKING LAYERS

The results of adding CeO$_2$ and Sb$_2$S$_3$ layers to a normal heated substrate Xerox plate (Plate #1) are shown in Figure 16. From the curves one can see that the additional CeO$_2$ and Sb$_2$S$_3$ layers have little or no effect on the dark decay characteristics of these plates either positively or negatively. The results for plate #2 were very similar to those of plate #1. In all cases a positively charged structure shows a much higher charge retention than a negative one. The minor variations between the negative curves or between the positive curves were not consistently reproducible and probably due to differences in plate history. From these curves one must conclude that whatever blocking layers exist in a xeroradiographic plate they are not significantly disturbed or changed by the addition of CeO$_2$ or Sb$_2$S$_3$ layers. This result is consistent with that of other researchers (mentioned earlier), in that additional blocking layers added to a xeroradiographic plate do not seem to change the tendency for positive charge retention to be superior to the negative.

While the level of dark current for negative charging is not significantly reduced by CeO$_2$ or Sb$_2$S$_3$, it is consistent with the level of dark current in a Saticon. The level of dark current in a Saticon is about 0.2 nA/cm$^2$ and relatively constant from $2 \times 10^5$ to $10^7$ V/m. This dark current if present in a 300 µm $\alpha$-Se plate (18.6 pF/cm$^2$) would cause a potential decay of 10.8 V/s. From Figure 16, negatively charged plates show a potential decay of 30 V/s at $2.7 \times 10^6$ V/m. This is in fair agreement with the Saticon value. It would seem, therefore, that CeO$_2$ and Sb$_2$S$_3$, if providing blocking action for negative charging, can only do so to the level found in a Saticon and not to the much lower level of a positively charged xeroradiographic plate (0.001 nA/cm$^2$ at $10^7$ V/m).

B. INVERTED TARGET

As a control the unmodified Xerox 125 plate used in this experiment was measured and is shown in Figure 17. The discharge curves show a good positive and poor negative charge retention which is consistent with Schaffert's curve of a heated substrate $\alpha$-Se plate (Figure 10). The initial decay rate is about 0.1 V/s which corresponds to $-0.0037$ nA/cm$^2$ and is consistent with Xerox 125 specifications$^5$ (0.16 V/s).
Figure 16. Dark decay for a-Se plates with additional CeO$_2$ and Sb$_2$S$_3$ blocking layers.
Figure 17. Dark decay of an unmodified Xerox 125 plate.

Figure 18. Dark decay of Xerox 125 plate with 4000 Å Indium.
The discharge curves for the Xerox 125 plate after coating with 1000Å of indium are shown in Figure 18. The addition of the indium electrode seems to increase the dark current for positive charging (0.16 V/s, 0.006 nA/cm²), however, this level of dark current is still low enough for use in a large area vidicon.

After bonding a new glass substrate to the surface and removal of the old Al substrate by etching, the discharge curves were again measured and are shown in Figure 19. As hoped there has been a reversal of the preferred polarity of the plate. Although the curves are not an exact reversal of those in Figure 18 the plate is clearly dominantly negative. The removal of Al from the Al/Al₂O₃/a-Se interface does not significantly change the blocking action at this interface. Blocking at this interface therefore seems to be due to electron trapping either in the Al₂O₃ or in the a-Se.

After the addition of 1000Å of Sb₂S₃ the plates were remeasured and the results shown in Figure 19. The additional Sb₂S₃ layer seems to have degraded the negative decay curve a little, but it is still within acceptable limits for use in a vidicon. Decay is 1.5 V/s at 1500V or 10⁷ V/m which corresponds to 0.056 nA/cm².

The ability to reverse the electrical characteristics of the a-Se plate supports the hypothesis that blocking action of the a-Se free surface and substrate interface is predominantly due to trapping. Trapping at the substrate interface may occur in either the a-Se or the Al₂O₃ or some intermediate layer. Further evidence to support the trap barrier hypothesis is shown in Figures 21 and 22. Figure 21 shows successive dark decay curves for positive charging. The decay curves show a decreasing dark current with each charge as more deep surface traps are filled. Bulk originated dark current can be ruled out as a mechanism since the a-Se plate exhibits a low residual potential. Any bulk dark current involves bulk defect ionization and residual space charge. Figure 22 shows that a previous negative charge on the plate severely increases the dark decay rate for subsequent positive charging. This behaviour is likely caused by space charge from the previous negative cycle disrupting the subsequent positive charge cycle. If space charge due to positive charging strengthens an existing barrier, then space charge from negative charging will weaken it. While the exact nature of the trap barrier is unknown it is clear, however, that the history dependent behaviour of the a-Se plate cannot be explained by Schottky barrier, insulating barrier, or unipolar conduction barrier action alone.
Figure 19. Dark decay of an inverted Xerox 125 plate.

Figure 20. Dark decay of an inverted Xerox 125 plate with 1000 Å Sb$_2$S$_3$.
Figure 21. Successive dark discharge curves for positive charging of a Xerox 125 plate.

Figure 22. Dark discharge curve of a Xerox 125 plate when positive charging follows negative charging.
An inverted target and control target were tested in the 6" demountable vidicon. The control target was not a Xerox 125 plate but was a xeroradiographic plate with similar decay properties. A plot of the dark current as a function of target potential for the control target is shown in Figure 23. The unacceptably high dark current found at voltages above 150V is to be expected from the low negative acceptance potential characteristic of the control. The inverted target showed a much lower dark current allowing the target potential to be raised to our goal of $10^7$ V/m or 1500V also shown in Figure 23. At 1500V the dark current is 1.9 nA (0.076 nA/cm²) which is consistent with the dark current measured xerographically. The dark current is well below the value at which dark current shot noise is a concern (~2500nA). Although defects were present the image overall was clear and showed no perceptible lag. The defects are most likely due to the non-cleanroom manner in which the target was made. The low lag is due to a low density of bulk traps, a property which is undisturbed when the inverted target is made. An x-ray image from the inverted target is shown in Figure 24.

C. UNHEATED SUBSTRATE TARGET

The dark discharge for positive and negative charging of both the unheated substrate as well as the heated substrate control are shown in Figure 25. From the curves, the most important observation is that not heating the substrate significantly increases the acceptance potential for negative charging. Negative acceptance potential increases from 1215V ($4 \times 10^6$ V/m) to 3960V ($1.3 \times 10^7$ V/m). By not heating the substrate, the acceptance field and dark current for negative charging make it acceptable for use in a vidicon.

The results of our experiment agree well with those of Schaffert (Figure 10). Comparing our curves with Schaffert's we find the following similarities. Not heating the substrate improves negative charging and degrades positive charging but positive charging remains better than negative. Also positive heated substrates perform the best while negative heated substrates perform the worst. One difference between our experiment and Schaffert's is that his heated negative plate is much worse than our heated negative plate. Perhaps this is due to a difference in actual substrate temperature (Schaffert 75°C, ours ~70°C). Schaffert's curves also show a greater initial decay followed by larger sustained dark current when compared to our curves. The exact reason for this is not clear. The lower initial decay of our plate may be due to higher quality a-Se with less impurities or traps. The difference in sustained dark current is probably due to a difference in substrate surface treatment.
Figure 23. Dark current of an inverted and normal Xerox 125 plate in the large area vidicon.

Figure 24. X-ray image of a human hand phantom obtained using the inverted Xerox target with $V_T = 1000$V.
Figure 25. Dark decay of an α-Se plate with heated and unheated substrate.
The unheated substrate α-Se plate has not been tried in the demountable vidicon at this time. While this plate may produce an acceptable vidicon target with low dark current there is reason to believe that other problems associated with the substrate not being heated may occur. It is known that unheated substrate plates have a higher density of bulk defects than heated substrate plates\(^2,66,67\). In the vidicon, this can lead to photoconductive lag and after-images. It is possible, therefore, that despite its low dark current the unheated substrate α-Se plate may not result in a satisfactory large area vidicon target.

V. CONCLUSIONS

Experiment has shown that a xeroradiographic plate made in the normal manner (heated substrate) and overcoated with Sb\(_2\)S\(_3\) does not produce a target suitable for use in an x-ray vidicon. The reason is that while such plates work well when positively charged, they exhibit very high dark currents when negatively charged in the vidicon. The higher dark current for negative charging has been shown to be due to leakage at one or both of the α-Se interfaces, and is not a bulk effect. These interfaces must therefore be changed. Modification of the xeroradiographic plate structure and process to make a viable vidicon target has yielded the following:

1. Insertion of additional CeO\(_2\) and Sb\(_2\)S\(_3\) layers to a xeroradiographic plate with normal heated substrate has little or no effect on blocking properties. Production of a negative plates was not possible by this method.

2. The procedure of inverting the target does produce a negative plate with a dark current that is almost as low as a normal positive Xerox plate. This plate was used successfully in the x-ray vidicon.

3. Not heating the target substrate during α-Se evaporation does reduce dark current for negative charging, however, it is not as good as the inverted target or a positively charged plate and probably has poor charge transit.

The results of these experiments support the trap barrier model. Using this model, the CeO\(_2\) and Sb\(_2\)S\(_3\) did not change the plate characteristics since the major blocking action was due to trapping inherent in the α-Se surface. Success of the inverted target is explained by having the inherent trap layers reversed in order which reverses the preferred polarity. The actual nature of the conductive substrate is of little importance. Also the temperature of the substrate during evaporation plays a very important role in determining the type and density of traps formed at the interfaces. All plates, heated or unheated substrate, tend to have predominantly hole traps on the surface and electron traps at the substrate. Heating the substrate increases this tendency.
While the process of inverting the α-Se plate produces a suitable target, it would be desirable to avoid the etching process. This can likely be accomplished by co-evaporation of impurities into the α-Se at the beginning and end of evaporation to force trap layers of the desired type.
REFERENCES


CHAPTER 6

A PROTOTYPE LARGE AREA X-RAY SENSITIVE VIDICON

I. INTRODUCTION

The two major problems encountered in developing a large area x-ray vidicon have been the instability in surface potential (crossover) caused by excessive secondary electron emission and excessive dark current caused when the surface of a xeroradiographic a-Se plate is charged negatively. A prototype large area vidicon has been valuable in developing solutions to these two problems (instability in Chapter 4, dark current in Chapter 5). With instability and dark current under control one can begin to characterize the vidicon in terms of signal, noise, resolution and lag. This chapter describes the construction of the prototype and presents some preliminary measurements of the prototype system to compare against predictions made in Chapters 2 and 3.

II. MATERIALS AND METHODS

A. VIDICON FABRICATION

The vidicon tube as shown in Figures 1 and 2 is of Pyrex glass construction with an outside diameter of 6 inches and a wall thickness of ~2.5 mm. The tube is demountable at two locations (using ground glass joints and vacuum grease) to allow internal components to be changed. Vacuum is maintained between $10^{-5}$ and $10^{-6}$ Torr during operation by permanent connection to an oil diffusion pump.

The tube can be used with either an electrostatically focussed electron gun or a magnetically focussed electron gun. For use with magnetic guns, an external focus coil was constructed with a mild steel core and copper coil which requires ~250 mA. The tube is magnetically deflected using a television CRT

* This chapter along with chapter 4 will form the basis of a paper to be submitted to *Medical Physics* on the practical implementation of a large area x-ray vidicon.
Figure 1. Photograph of the 6" demountable x-ray vidicon tube.

Figure 2. Schematic of the 6" demountable x-ray vidicon tube.
deflection yoke. Additional tube electrodes are fabricated from soldered brass. In the region of the deflection yoke, it was found necessary to make the internal electrode out of #302 stainless steel, 0.003" thick, in order to reduce eddy currents that are induced in the electrode which in turn disrupt the horizontal deflection field. Meshes are purchased as a sheet (0.001" Ni with 333 lines per inch) and are stretched over and secured to brass support rings with vacuum epoxy.

The a-Se target is a modified Xerox 125 plate which has a photoconductor thickness of 150 μm and a useful imaging area of 4" diameter. A Xerox 125 plate is normally charged positively and will exhibit excessive dark current if charged negatively as is required in the vidicon. The modification which allows negative charging involves inverting the a-Se structure. The inverted a-Se structure is made by evaporating an indium electrode onto the Xerox 125 plate surface followed by bonding of a glass substrate (~2 mm thick) to the indium. The original aluminum substrate is removed using HCl to reveal a new free surface. Details on the inverted target are given in Chapter 5.

Electrical stability of the a-Se surface is insured by the presence of a suppressor mesh next to the surface in addition to the field mesh normally found in vidicons. To reduce secondary electron emission and help maintain electrical stability of the a-Se surface during electron beam scanning, a layer of porous Sb$_2$S$_3$ is evaporated on the free surface. While a suppressor mesh could be used alone the Sb$_2$S$_3$ layer allows the suppressor mesh to be set at a higher potential and, therefore, be placed further from the target surface for a reduced capacitance and amplifier noise. Details of the Sb$_2$S$_3$ suppressor coating and suppressor mesh are given in Chapter 4.

The demountable x-ray sensitive vidicon system is shown in Figures 3 and 4. The camera control unit and preamplifier are taken from a Picker Model 3036-G fluoroscopic television system and are modified for use with the large area vidicon tube. The system produces RS-170 standard video, that is, 525 lines (483 active) with 30 frames per second interlaced. A high voltage bias circuit is needed to capacitively couple the preamplifier to the vidicon target which can be biased up to 5000V. Both the bias circuit and preamplifier are mounted in close proximity to the vidicon tube.

The electron gun control allows full adjustment and monitoring of the electron gun filament and grids. A deflection control unit was also constructed to allow full adjustment of the raster size as well as vertical and horizontal shift. The video image can be viewed on the monitor as well as be recorded on the video cassette recorder.
Figure 3. Photograph of the 6" demountable x-ray vidicon system.

Figure 4. Schematic of the 6" demountable x-ray vidicon system.
B. VIDICON CHARACTERIZATION

Signal current from the x-ray vidicon was measured both as a function of bias potential and x-ray exposure rate. The average signal current was obtained by measuring the potential across the target bias resistor. A comparison was made to the predicted signal current for the conditions used.

The preamplifier used in the prototype system at this time is from a 1" light sensitive vidicon camera and as such is not matched to the higher target stray capacitance of the prototype (65 pF). Amplifier noise is therefore higher than that obtainable with a matched preamplifier. The system was tested with both the Leeds noise phantom (N2) and Leeds step wedge phantom (GS2). Both phantoms were used at 70 kVp with 1 mm Cu filtration as recommended.

Three types of electron gun have been tested in the prototype vidicon and are shown in Figure 5. The potentials applied to the different vidicon grids are not critical with imaging possible over a wide range of values. The potentials used on the different grids of the prototype vidicon during resolution measurements is given in Table 1.

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<thead>
<tr>
<th>Grid Type</th>
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<tr>
<td>G2</td>
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<td>Target</td>
<td>V_T</td>
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Table 1. Potentials used in the prototype large area vidicon during resolution measurements.

Resolution was evaluated using a lead bar pattern in both the vertical and horizontal directions. MTF in the horizontal direction was also measured using a 150 μm wide x-ray slit. An average of 100 video lines through the slit was obtained using a digital storage oscilloscope and the result was Fourier transformed in a computer. The experimental MTF was then compared to the theoretical MTF for a cosine squared beam profile. Resolution of the system in zoom mode was evaluated using bar patterns in the vertical and horizontal directions and spatial linearity was evaluated using a 1 cm wire grid. Lag was also evaluated qualitatively by looking for the presence of blur behind a moving object.
Figure 5. Three types of electron gun used in the 6" demountable x-ray vidicon. Top: a magnetic focus gun from a 1" light sensitive vidicon, Middle: an electrostatic focus CRT gun and Bottom: an electrostatic focus CRT gun that has been modified to a magnetic focus gun.

Figure 6. Signal current versus target potential for the 6" demountable x-ray vidicon with inverted a-Se target.
III. RESULTS AND DISCUSSION

A. SIGNAL PROPERTIES

The signal current obtained from the prototype x-ray vidicon versus target potential is shown in Figure 6. The curve shows a near linear increase in signal with target potential. The small deviation from linearity for potentials above 1800V is due to dark current. The nominal operating potential of the target (150 μm a-Se) however, is 1500V for which dark current is not a problem. The deviation from linearity below 500V is a well known characteristic of xeroradiographic a-Se layers. The electric field dependence of a-Se x-ray sensitivity is believed to be a result of geminate recombination. Bound electron-hole pairs (excitons) created by x-ray absorption are pulled apart by the electric field preventing recombination. As the electric field is increased, a greater percentage of bound electron-hole pairs are released, but the percentage released is not linear with field. An empirical relationship for this effect is given in Chapter 7 (Equation 1). The 1” x-ray vidicon described earlier shows a similar signal versus target potential characteristic (Chapter 4, Figure 12). The near linear increase in signal current in Figure 6 also agrees with the results obtained from the 1” x-ray sensitive vidicon of Maruyama et al (Chapter 5, Figure 13). Both show that an increase in signal current is possible if the target potential can be increased without excessive dark current.

The measured signal current versus x-ray exposure rate curve is shown in Figure 7. The curve is linear within the measured range of 25 to 250 nA. The slope of the curve is 22.3 nA/(mR/s) which is the x-ray sensitivity of the vidicon at 70 kVp with 10 mm Al added filtration and $V_T=1000V$. The signal current of Figure 7 is the average signal current measured at the bias resistor as opposed to the instantaneous readout current measured at the video output. These two currents differ by the terms $K$ and $\Psi$ as described in Chapter 2. The expected sensitivity of the prototype vidicon can be calculated using Equation 1 of Chapter 2 by setting $K=1$ and $\Psi=1$ to give the average instead of the instantaneous current. Using the values $X=0.857$ mR/s (1 mR/s at input plane = 0.857 mR/s at a-Se plane due to magnification), $\eta=0.15$ (Q.E. for 150 μm a-Se at 70 kVp, 10 mm added Al and 4.5 mm glass window + substrate), $A=69.4$ cm$^2$, $\varepsilon=36.9 \times 10^3$ eV and $W=75$ eV ($E=6.7 \times 10^6$ V/m), we predict an average current of 19.6 nA (per 1 mR/s at input plane). This is close to the measured value and indicates that the signal current of future vidicons can be accurately predicted. The sensitivity of an XRII/TV system of the same image diameter is about 400 nA/(mR/s) [instantaneous] (60 nA at 150 μR/s) which converted to an average current is 178 nA/(mR/s) [average] ($K=1.33$, $\Psi=1.7$). This is about 8 times ($178/22.3=7.98$) higher than the prototype.
Figure 7. Signal current versus x-ray exposure rate for the 6” demountable x-ray vidicon with inverted a-Se target. Signal current refers to average signal current which may be multiplied by 2.26 to get instantaneous signal current.

Figure 8. X-ray image of the Leeds step wedge (GS2) made at 70 kVp with 1 mm added Cu. All steps in the wedge are visible.
The sensitivity of the prototype could be increased to match the XRII/TV system by increasing the a-Se thickness from 150 µm to 500 µm, by increasing the a-Se electric field to 10^7 V/m or higher and by changing the input window and substrate (4.5mm glass to 1.2 mm Al).

B. NOISE PROPERTIES

When the prototype vidicon was initially tested, it was found that shielding of the target was necessary to exclude external interference. Interference from the horizontal deflection circuit was particularly troublesome. Bypass capacitors on the suppressor mesh, field mesh and drift electrode also helped to reduce external noise. The stray capacitance of the target was measured to be 65 pF which when coupled to the preamplifier of a 1" vidicon yielded a noise of 3.9 nA rms in 5 MHz. The preamplifier uses three 2N4416 JFET transistors ($e_n=1.7$ nV/(Hz)^{0.5}, $C_p=4$ pF per JFET) and has $R_s=500$ kΩ. Using Equation 12 of Chapter 2, along with $B=5$ MHz, the theoretical Johnson noise of the amplifier is 0.41 nA rms in 5 MHz. Using Equation 16 of Chapter 2, along with $e_n=0.98$ nV/(Hz)^{0.5} (1.7/3)^{0.5}=0.98), $C_s=77$ pF (($4\times 3)+65=77$) and $B=5$ MHz the theoretical amplifier noise of the preamplifier is 3.1 nA rms in 5 MHz. The combined theoretical Johnson and amplifier noise, is therefore, 3.12 nA rms in 5 MHz. ($3.1^2+0.41^2=3.12$). The majority of the measured noise can, therefore, be accounted for by amplifier noise. The difference between the measured and theoretical noise is possibly due to external interference, JFET transistors with higher noise than specified in the data sheet or noise above 5 MHz being included in the measurement since the filter defining the bandwidth does not have a sharp cut-off. If a matched preamplifier were used with the prototype, for example nine, J309 JFETs in parallel ($e_n=1.2$ nV/(Hz)^{0.5}, $C_p=7$ pF per JFET) the amplifier noise would be about 2.1 nA rms in 5 MHz ($C_s=128$ pF, $e_n=0.4$ nV/(Hz)^{0.5}) which is about twice that of a typical 1" vidicon camera.

The prototype was tested with the Leeds noise phantom (N2) which consists of various 1.1 cm diameter discs of different x-ray contrast. Using the prototype, discs with contrasts as low as 4.5% were detected. The Leeds test guidelines state that a fluoroscopic system should be capable of detecting a disc of 4% contrast or less. A matched preamplifier will probably allow this criterion to be met. The prototype was also tested with the Leeds step wedge (GS2). This phantom contains steps of fractional x-ray transmission ranging from 0 to 1.0 of peak white in 0.1 increments when used at 70 kVp and 1 mm Cu filtration. The phantom also contains two discs of transmission 1.0 and 0 within squares of transmission 0.9 and 0.086 respectively. An x-ray image of the step wedge made with the prototype is shown in Figure 8 (7 steps and 1 disc shown). All steps of the step wedge were visible using the prototype vidicon.
Indications are that the noise of a full 9" x-ray vidicon should be close to that predicted in Chapter 2 and that it should successfully pass the Leeds tests.

C. RESOLUTION PROPERTIES

The first electron gun tested in the prototype vidicon was the electrostatic CRT gun (Figure 5). This gun has a crossover diameter of $-30 \, \mu m$ and has a magnification of $-15$ when used in the prototype vidicon (Chapter 3, Figure 9, $a=2$ cm, $b=30$ cm). The beam spot diameter at the target for this gun is, therefore, about $450 \, \mu m$. While this beam spot is larger than desired for 480 lines in 4" (~200 $\mu m$ line spacing) the gun worked well, allowing many low resolution experiments to be conducted. The experiments on target stability and dark current described in Chapters 4 and 5 respectively, were made using the electrostatic CRT gun. If maintained under vacuum, the gun could be used for a long period of time. The gun will only last 2 or 3 air-vacuum-air cycles, however, before its emission becomes too low to use.

To increase resolution, the prototype was fitted with a magnetic focus coil and a magnetic focus gun cut from a used 1" vidicon. Such a gun has a G2 aperture of $-30 \, \mu m$ and a magnification in the prototype vidicon of about 4 ($a=7.4$ cm, $b=30$ cm). The beam spot diameter for this gun is, therefore, about 120 $\mu m$ which provided improved resolution over the electrostatic CRT gun.

Due to a lack of available 1" vidicon guns the electrostatic CRT gun was modified to be a magnetic focus gun. This was done by removing the G5 electrode (Chapter 5, Figure 7), extending the G4 electrode with a brass tube and electrically connecting the G3 and G4 electrodes. An aperture of $-2 \, mm$ was placed in the brass extension tube to limit the beam diameter in the lens. The beam spot diameter for this gun is about 120 $\mu m$. This spot size was chosen to provide good resolution in zoom mode and is smaller than that required in the full field of view. To produce a larger beam spot, the electron gun can be defocussed slightly. If a beam spot is used which is smaller than the line spacing then the unscanned regions of the target between the lines will develop at higher potential than the scanned regions. This will have the effect of defocussing the beam as it approaches the target surface such that in equilibrium, the effective beam spot diameter is equal to the line spacing. This technique of letting the beam adjust itself, however, may have the deleterious side effect of causing a flickering between adjacent lines$^1$. Small electromagnetic alignment coils were placed near the G2 electrode and near the entrance of the focus coil. These coils were adjusted to minimize astigmatism and coma while maximizing beam current. The modified CRT gun worked well and was used during the resolution measurements that follow.
Figure 9. X-ray image of a bar pattern to evaluate horizontal resolution. Limiting horizontal resolution is about 2.87 lp/mm in normal (non-zoom) mode.

Figure 10. X-ray image of a bar pattern to evaluate vertical resolution. Aliasing limits vertical resolution to about 1.88 lp/mm in normal (non-zoom) mode.
An evaluation of resolution using a bar pattern is shown in Figure 9 for horizontal resolution, and in Figure 10 for vertical resolution. Limiting horizontal resolution is about 2.87 lp/mm. This resolution limit is a result of the finite beam spot diameter and the electrical bandwidth of the amplifier chain. A spatial frequency of 2.87 lp/mm corresponds to a temporal frequency of 7.3 MHz. Aliasing of the pattern in Figure 10 occurs at about 1.8 lp/mm. This is in agreement with the theoretically expected resolution of 1.7 lp/mm for 480 lines in 4" (Chapter 3, Equation 1, S=525, a=0.92, K=0.7, d.=100 mm). The horizontal MTF measured using an x-ray slit is shown in Figure 11 along with the theoretical MTF for a cosine squared beam profile. The theoretical MTF is given by Equation 3 of Chapter 3 using r'=0.1125 mm, which is based on the measured line spacing of 225 μm and the electron gun adjusted for best focus. The measured MTF was corrected for the aperture response of the 150 μm x-ray slit and for the frequency response of the amplifier chain. From Figure 11, it can be seen that the measured MTF falls below the theoretically predicted MTF, the cause for which is unknown at this time. Veiling glare behind a 10% area lead disc (3.2 cm) was only 3% to 4% of the background, which means that x-ray scatter is unable to explain the difference. A possible explanation is that the beam spot is larger than expected due to some aberration of the electron-optical system. The theoretical MTF for a beam spot of 300 μm would come close to the measured MTF. This explanation seems to be in conflict, however, with the fact that the vidicon can achieve much higher resolution by zooming (reduce scan amplitude). Another explanation is that the beam profile has a relatively narrow central region but also has long tails extending outward at its base. This would reduce the MTF at medium spatial frequencies (~1.5 lp/mm) but still have significant modulation at high spatial frequencies (~5 lp/mm).

The MTF was also measured using a lead bar pattern. The square wave response was measured using an oscilloscope and the square wave response was converted to MTF. The MTF measured this way was in agreement with the MTF measured by the x-ray slit method. A star pattern image was also made and is shown in Figure 12. The star pattern allows both horizontal and vertical resolution to be evaluated quickly in the same image. Modulation of the vertical lines can be seen at a radius of 6.8 mm or greater and unaliased modulation of the horizontal lines can be seen at a radius of 8.6 mm or greater. Limiting horizontal resolution is, therefore, ~2.8 lp/mm (1/(6.8 mm x 1.5° x 2 x (π/180))) while limiting vertical resolution is about 2.2 lp/mm. These values are in agreement with those obtained using the bar pattern.

By reducing the horizontal and vertical scan amplitude, the x-ray vidicon can be zoomed to a smaller subsection of the target. Zoom images of the bar pattern to evaluate horizontal and vertical resolution are shown in Figures 13 and 14 respectively. In both the horizontal and vertical directions, resolution exceeds 4.87 lp/mm. This demonstrates the high intrinsic resolution of the a-Se layer. It also indicates that a
Theoretical MTF for a 225 prn dia. FWHM cos^2 beam spot

Measured MTF corrected for aperture response of 150 μm x-ray slit and amplifier response

Figure 11. Measured and theoretical MTF for the prototype x-ray vidicon.

Figure 12. X-ray image of a star pattern.
Figure 13. Zoom mode x-ray image of a bar pattern to evaluate horizontal resolution. Limiting horizontal resolution is above 4.86 lp/mm.

Figure 14. Zoom mode x-ray image of a bar pattern to evaluate vertical resolution. Vertical resolution exceeds 4.86 lp/mm.
substantial improvement in resolution can be made in an x-ray vidicon by increasing the number of scan lines from 525 to 1000 or 2000. The white border on the images is a result of x-ray absorption in the unscanned parts of the target which build up a high potential and pull the beam. This could be eliminated by collimating the x-ray beam to fall within the image area (required by law when patients are imaged) or by using a flood electron gun during retrace to limit the potential rise of the unscanned areas (Chapter 4). An x-ray image of a 1 cm wire grid used to evaluate spatial linearity is shown in Figure 15. Most of the distortion in the image is a result of crude electron-optical construction and stray magnetic fields. The cold cathode (Penning) vacuum gauge behind the vidicon was a major source of stray magnetic field. The distortion in the upper right of the image is the result of a mechanical defect in the collimator lens. The field mesh cylinder is flattened in this area which distorts the field between it and the drift cylinder (Figure 2). Proper collimator lens action, therefore, does not occur in this region.

A small amount of barrel distortion is present in the monitor image, which is the result of pincushion distortion in the vidicon scan (monitor is corrected for distortion). Without a collimator lens the vidicon scan has pincushion distortion due to geometrical effects (Chapter 3, Deflection Abberations). The addition of a collimator lens introduces barrel distortion, which in our case, does not fully compensate the pincushion distortion of the vidicon scan. In future vidicons, distortion could be corrected by either designing the collimator lens for full compensation or by modifying the current waveform in the deflection yoke. Fortunately, the a-Se receptor is flat and does not have the severe pincushion distortion characteristic of an XRl, which has a curved input receptor.

If the collimator lens is not adjusted properly ($V_D$, $V_F$ ratio) persistent rippling (Chapter 3, Non-Perpendicular Beam Landing Effects) can occur at the edge of the target as seen in Figure 8 (also Chapter 5, Figure 24). With proper adjustment, however, persistent rippling is eliminated as seen in Figure 12 and 15 (also Chapter 4, Figure 18).

In the prototype, the electrode cylinder between the field mesh and suppressor mesh is the same diameter as the image area. In retrospect, it was realized that this cylinder should have a larger diameter so that near the edge of the image area, the perpendicular electric field between the meshes will not be disturbed. This would aid in making the beam trajectory as perpendicular as possible at the edge, and minimize any edge related distortion. This recommendation also applies to the electrode cylinder between the suppressor mesh and target surface.
Figure 15. X-ray image of a 1 cm wire grid to evaluate spatial linearity.
Image artifacts due to mesh vibration were not a problem even with the mechanical roughing pump operating. Image modulation in the form of horizontal bands could be caused by striking the camera structure with a sharp blow. This was well in excess of any jostling expected in normal operation. Moire effects between the two meshes were also not a problem when the meshes were aligned at 45° to each other.

D. LAG PROPERTIES

Real time x-ray images with no perceptible lag have been demonstrated with the prototype x-ray vidicon. Although not quantitative, these image sequences indicate that low lag should be achievable in future vidicons.

Lag has been seen in the prototype in three unfavourable situations. One situation, as described in Chapter 4, occurred when the porous Sb$_2$S$_3$ layer was too thick. Trapping in the Sb$_2$S$_3$ layer can delay the change in target surface potential when x-rays are absorbed (photoconductive lag). Another situation causing lag occurs if the cathode temperature is too high. This is purposely done in the demountable vidicon to boost the cathode emission when the gun is reused after contact with air. In this case, the higher cathode temperature results in a larger spread in energy of the beam electrons (beam discharge lag). Finally, long term lag or burn-in occurs if the electric field within the a-Se layer is less than about 5x10$^6$ V/m.

IV. CONCLUSIONS

The prototype vidicon has provided much valuable information that will aid in the construction of a full sized (9" or greater) x-ray vidicon. It has demonstrated that crossover can be prevented by the use of a suppressor mesh and low δ surface coating. It has also demonstrated that an a-Se layer can be made and used which has a low dark current for negative surface charging. Signal and electronic noise measured in the prototype are close to theoretical values, indicating that the predicted signal and noise for a 9" vidicon should be valid. High resolution was demonstrated, especially in zoom mode where greater than 4.87 lp/mm could be seen. Some discrepancy exists between the theoretical and measured MTF which requires further investigation. Finally, real time images have been demonstrated which show no perceptible blur for moving objects, indicating that low lag imaging should be possible in a full sized vidicon.
REFERENCES

CHAPTER 7

FUTURE WORK AND CONCLUSIONS

I. FUTURE WORK

The 6" prototype system has shown that it is possible to utilize thick a-Se layers in a vidicon with large target potentials and has provided information for future designs. This prototype, however, is crude and images produced are inferior to a modern XRII/TV system. The immediate goal for the future is to build a 9" x-ray vidicon that will produce images of the highest possible quality for direct comparison to a 9" XRII/TV system. To do this the a-Se target thickness will be increased to 500 μm and clean room conditions will be used during target construction to eliminate defects. The electron optics will be machined precisely and the electron gun will be custom made to match the resolution and beam current requirements. The preamplifier will be matched to the target stray capacitance for lowest noise and the scanning will allow both 525 and 1000 line readout.

In chapters 2 and 3 it was shown that a 9" diameter 500 μm thick a-Se layer with an electric field of $10^7$ V/m can provide signal to noise ratio, resolution, and low lag sufficient for medical fluoroscopy. While a 9" x-ray vidicon has been shown to be quantum noise limited at exposure rates and resolutions relevant to medical fluoroscopy, it is only so by a small margin. An increase in signal or decrease in electronic noise would allow a larger, more comfortable margin to be realized. Some possible improvements to the x-ray vidicon include:

1) Increasing the signal by increasing a-Se photoconductor potential
2) Increasing signal and x-ray absorption by using an alternative photoconductor
3) Reducing noise by a change in the preamplifier design or a reduction in target stray capacitance
4) Increasing SNR by use of a return beam readout
5) Reducing the tube length

These possibilities will now be discussed.
A. INCREASING AMORPHOUS SELENIUM GAIN

Most photoconductors exhibit a saturated photocurrent for light and x-rays as the electric field in the photoconductor is increased. This saturation corresponds to full collection of the e-h pairs created and also represents a minimum value for $W$. Klein predicts that the theoretical value of $W$ at saturation is $-3E_e$. For example, PbO has $E_e=1.9$ eV and shows signal saturation at about $2\times10^6$ V/m where it has a $W$ of 8 eV. A-Se does not show a saturation in signal current at practical electric fields, also $W$ is much larger than $3E_e=3\times(2.1$ eV$)=6.3$ eV. The reason for a high value of $W$ at fields where other photoconductors show saturation ($10^7$ V/m) is believed to be caused by geminate recombination.

In Xeroradiography the value of the electric field used is $10^7$ V/m where the value of $W$ is 50 eV. $W$ is known to decrease with $E>10^7$ V/m, however use of these high fields creates problems with respect to high dark current and defect spots. $W$ has been measured for xeroradiographic a-Se in the range of $E=10^6-10^7$ V/m where it obeys the empirical relationship:

$$W=W_o\left(\frac{E}{E_0}\right)^\gamma$$  \hspace{1cm} (1)

With $W_o=50$ eV, $E_o=10^7$ V/m and $\gamma =0.6$ to 0.8

For practical purposes this formula is adequate to predict the signal current in an x-ray vidicon for electric fields between $10^6$ and $10^7$ V/m. At present xeroradiographic a-Se layers are limited by dark current to an electric field of about $10^7$ V/m. Improved blocking layers will be required to increase the electric field above this point. Using thin a-Se layers Tanioka et al have been able to increase the electric field in a-Se to about $10^8$ V/m at which point avalanche gain is observed. With this same technology, Maruyama et al have demonstrated an x-ray vidicon with $E>10^8$ V/m (see Chapter 5, Figure 13). They show a near linear increase in signal current for electric fields between $10^7$ and $10^8$ V/m. If we assume $W=50$ eV at $10^7$ V/m then near $10^8$ V/m we should be close to the theoretical minimum value of $W=6.3$ eV predicted by Klein. A significant increase in signal should therefore be possible by the improvement of blocking contacts in thick xeroradiographic a-Se layers along with an increase in target bias. A field of $3\times10^7-8\times10^7$ V/m is high enough that it would significantly increase the signal obtained, but low enough to avoid the complications (dark current, uniform gain) of the avalanche region. If such an x-ray vidicon target could be made, then its signal and signal to electronic noise ratio will be superior to that of the XR11/TV system.
1) **Avalanche Gain**

Avalanche gain occurs when a carrier gains enough energy from the electric field to generate an additional electron hole pair during a collision. This kind of chain reaction depends strongly on electric field and on the $a$-Se thickness. To obtain uniform gain the target must be of uniform thickness and the target voltage well regulated. Gains up to 10X have been reported for 2 $\mu$m $a$-Se and up to 100X for 8 $\mu$m $a$-Se. This technology has been called HARP for high gain avalanche rushing photoconductor and the resulting vidicon is called a Harpicon. Most of the work in avalanche gain has been with light sensitive tubes however, use of a Harpicon with x-rays has been reported$^8$ where a signal gain of 40X was demonstrated.

To be of medical value thick $a$-Se layers are required. It is unlikely that a straight forward increase in electric field to $10^6$ V/m (assuming proper blocking contacts) will produce controlled gain. Tanioka$^{7,9}$ has shown that as the $a$-Se is made thicker the avalanche gain versus electric field rises very sharply. For thick x-ray layers of $a$-Se it may not be practically possible to control the gain uniformly across a wide area. Furthermore, since x-ray photons are absorbed at different depths in the $a$-Se layer, each photon would have a different gain. This will result in greater noise when compared to a target with constant gain.

An alternative approach used in silicon avalanche photodiodes is to have separate collection and avalanche regions. The collection region constitutes the majority of the thickness of the layer and has an internal electric field below the threshold for avalanche. Carriers generated in the collection region are brought to the relatively thin high field avalanche region where the number of carriers is multiplied. The difference in electric field in the two regions could be achieved by appropriate doping. Since the avalanche region ($E>10^4$ V/m) is much thinner that the collection region ($E<10^8$ V/m) the increase in target voltage is minimal when avalanche is employed. The increased signal from avalanche gain could provide a tremendous advantage to a large area x-ray vidicon.

**B. ALTERNATIVE PHOTOCONDUCTORS**

Throughout this thesis we have assumed the x-ray photoconductor of the large area vidicon to be $a$-Se. Although $a$-Se is not ideal it does meet the requirements for medical fluoroscopic use. Any alternative to $a$-Se must meet the requirements of high absorption, high sensitivity, low dark current, low layer
capacitance, uniformity, long life, and an ability to be made in large areas. While many of the
photoconductors can surpass $\alpha$-Se on one or two of these parameters, very few are sufficient in all respects
that they could be used for medical fluoroscopy.

The weakness of $\alpha$-Se lies in its less than ideal x-ray absorption and sensitivity. For the other parameters, $\alpha$-Se is almost ideal. While $\alpha$-Se can be adapted to the x-ray vidicon with a minimum of materials research, other photoconductors will require more extensive development. Promising x-ray photoconductors include PbO, CdSe, CdTe, CdZnTe, and TlBr which will now be discussed.

1) **PbO**

PbO is a photoconductor which has been in use for some time. The first use in an x-ray vidicon was reported by Heijne$^{10}$ in 1954. These reports were for x-ray irradiation of the light sensitive Plumbicon$^{2,11}$ developed by Heijne of Philips (see Chapter 1). A large area x-ray vidicon using PbO was made by Jacobs and Berger$^{12}$ of GE in 1956 and was called the "X-icon". The tube was 8" in diameter and had a 150 $\mu$m thick layer of PbO. Unfortunately degradation of the thick PbO layer by x-ray irradiation quickly limited the tubes lifetime (see Chapter 1). Suzuki$^{13}$ of Hamamatsu in 1976 reported 1" and 5" PbO x-ray vidicons using 15 $\mu$m PbO. Today 1" and 2" PbO x-ray vidicons are commercially available from Hamamatsu (N603 and N400). The small size and low x-ray absorption however limits the use of these tubes to non-destructive testing (see Chapter 1).

Most of the work with PbO has been for the light sensitive Plumbicon$^{2,11}$. The tube target has a PIN structure which is typically 12-20 $\mu$m thick and biased to 50 V. The P and N regions are obtained by doping the PbO while the intrinsic region is obtained by making the PbO porous. Porosity is achieved by evaporating the PbO in a residual oxygen atmosphere of $1 \times 10^{-3} - 20 \times 10^{-3}$ Torr$^{14,15}$. Porosity of the layer$^2$ is ~50%.

The potential applied to the target is dropped mostly across the intrinsic region. The high electric field in this region sweeps carriers across the target quickly resulting in a rapid response and minimal recombination. The PIN structure blocks surface injection of carriers, and combined with the wide band gap of 1.9 eV, also limits bulk thermally generated dark currents resulting in a very low dark current. Plumbicons typically have <1 nA/cm$^2$ dark current$^{14}$, similar to $\alpha$-Se. Plumbicons are noted for having very low lag, typically <5% in the third TV field (3TVF, 50 ms). This degree of lag is comparable to the lag of a Saticon and in both cases is dominated by beam discharge lag and not the photoconductor itself.
The most attractive feature of PbO as an x-ray photoconductor is the high atomic number of Pb (Pb:Z=82)(O:Z=8). This advantage is diminished however by the fact that the PbO layer must be porous. The sensitivity of PbO is superior to that of α-Se. Klein\(^1\), as well as Dearnley and Northrop\(^16\), report that \(W=8\) eV for crystalline PbO (compared to \(W=50\) eV for α-Se).

A disadvantage of PbO is that it is difficult to manufacture. A PbO layer will react immediately with ambient air causing both its dark resistance\(^14\) and its x-ray sensitivity\(^17\) to decrease. A more serious problem with thick PbO layers is the degradation with use characterized by: image persistence; non-uniformity; white spots; and decreasing sensitivity\(^18,15\). Degradation does not occur if x-rays are present without an electric field. The phenomenon was attributed by Bigelow and Haq\(^15\) to a loss of oxygen on the crystallite surfaces during irradiation. No further studies or solution to this problem has been found in the literature. The thin layers used by Suzuki\(^14\) and Hamamatsu tubes apparently do not suffer from x-ray fatigue. According to Jacobs\(^19\) the long life of Suzuki’s tubes are related to their low sensitivity.

With the exception of the fatigue problem encountered by Jacobs and Berger, PbO is an excellent x-ray photoconductor. It is quite possible that future materials research will yield a thick PbO layer that is free of fatigue effects.

2) **CdSe**

CdSe (Cd:Z=48)(Se:Z=34) is used in the commercially available Chalnicon\(^20,21,22\) where the sensitivity to light is greater than 3 times that of the Plumbicon or Saticon. Dark current is very low\(^23,24\), (0.1 nA) and is comparable to the Plumbicon and Saticon. Lag is about 10% in 3 TVF\(^24\) making it quite a bit worse than the Plumbicon or Saticon but not as bad as the Sb\(_2\)S\(_3\) vidicon. The high lag is attributed to beam discharge lag because of the high capacitance of the thin target. The target is prepared by the evaporation of CdSe onto ITO forming a polycrystalline CdSe layer ~5 μm thick. The surface is oxidized to form CdSeO\(_3\) and a final layer of As\(_2\)S\(_3\) is added to reduce secondary emission. A bias of 35 to 40 V is typical.

A 1" x-ray sensitive version of the Chalnicon (Pasecon) is made by Heimann (XQ1175) and also by Hamamatsu (N3131/E5273). No information is given on the CdSe thickness but it is probably comparable to that of the light sensitive Chalnicon. No reports of thick CdSe for x-ray use have been found. It remains to be seen whether targets thick enough for medical use can be made. The greatest challenge will be to produce both e and h ranges that exceed the photoconductor thickness.
3) \textbf{CdTe}

Single crystal CdTe has a relatively low W of 4.5 eV\textsuperscript{1.16} and a high average atomic number (Cd:Z=48)(Te:Z=52) promoting its use as a photon counting radiation detector. No commercially available light sensitive tube uses CdTe. Tomita et al\textsuperscript{17} and Hatanaka et al\textsuperscript{25} have recently produced 1" x-ray sensitive vidicons using sputter deposited polycrystalline CdTe. They were able to show that an 8 \mu m CdTe layer was capable of more than 3 times greater x-ray sensitivity than a comparable PbO tube. The sputter deposition technique produces CdTe layers which have a columnar structure (columns 0.3-1 \mu m in diameter). The layers are dense and stable in air.

Two disadvantages of polycrystalline CdTe at this time are its dark current and lag. Dark current is reported as <10 nA/cm\textsuperscript{2}. While this dark current could be tolerated in a 1" tube, it could prove problematic in a large area tube especially if the dark current is non uniform or time varying. The lag was reported to be 20% in 50 ms (3TVF). This is as high as the lag in a common Sb\textsubscript{2}S\textsubscript{3} vidicon still used in many XRII/TV fluoroscopic systems. While tolerable for slow moving GI applications, 20% lag would be quite objectionable for faster moving cardiac applications. The polycrystalline CdTe x-ray photoconductor is still in its infancy and improvements in dark current, lag, and thickness are likely to occur. Again the greatest challenge will be to produce both e and h ranges that exceed the photoconductor thickness.

4) \textbf{CdZnTe}

Cd\textsubscript{1-x}Zn\textsubscript{x}Te (Cd:Z=48)(Zn:Z=30)(Te:Z=52) is a useful photoconductor in either its amorphous or crystalline form. In its amorphous form \textit{a}-CdZnTe is used in the commercial vidicon called the Newvicon\textsuperscript{26}. In the Newvicon an additional ZnSe layer is added to prevent crystallization of the \textit{a}-CdZnTe by the ITO substrate. The ZnSe is transparent to light and primary photogeneration occurs in the CdZnTe layer. It has a high dark current of 6 nA/cm\textsuperscript{2} and lag of 10% in 3 TVF. The lag is mostly beam discharge lag and could be reduced with a thicker layer. No reports of thicker \textit{a}-CdZnTe layers have been found.

Single crystal Cd\textsubscript{1-x}Zn\textsubscript{x}Te, with x \approx 0.2 is recently promising to be an important room temperature single photon counter with possible application as a gamma camera. New purification techniques can produce single crystals as large as 10 cm in diameter which are nearly intrinsic without the use of dopants. Dark current is reported to be about 1 nA/cm\textsuperscript{2} for a 1.5 mm thick sample and 50V of bias\textsuperscript{27}. W is also estimated at 5 eV\textsuperscript{28} and good collection efficiency has been reported for layers as thick as 2 mm.
5) **TlBr**

Thallium Bromide (Tl:Z=81)(Br:Z=35), is a crystalline semiconductor which shows great promise as an x-ray photodetector. It has a wide band gap ($E_g=2.7$ eV), a $W$ of 6.5 eV and very high effective $Z$. Rahman et al. and Shah et al. have produced single crystal wafers 1" in diameter and 300-1300 μm thick. Bias voltages of up to 500V with a dark current of ~8 nA/cm² at 100V were used. TlBr shows good e and h transport at room temperature. This is important to prevent space charge build-up and subsequent loss of sensitivity. Other thallium halides such as TICl and TII show only e transport. As a photoconductor for an x-ray vidicon the problems lie with the relatively large dark current and producing large diameter wafers.

A problem that severely limits the choice of photoconductor in a large area vidicon is the capacitance of the photoconductor layer. If this capacitance is too high, it will lead to beam discharge lag, and real time readout will not be possible. (See Chapter 3) The capacitance of the layer is related to its thickness and dielectric constant ($\varepsilon_r$). Shown in Table 1 are different x-ray photoconductors along with their values of $\varepsilon_r$, thickness for 75% absorption ($d_{75}$) at 90 kVp and capacitance of the 75% absorption layer.

<table>
<thead>
<tr>
<th>Photoconductor</th>
<th>$d_{75}$ [μm]</th>
<th>$\varepsilon_r$</th>
<th>$C_{75}$ [nF]</th>
<th>$E_{typical}$ [V/μm]</th>
<th>$V_{75}$ [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$-Se</td>
<td>650</td>
<td>6.3&lt;sup&gt;32&lt;/sup&gt;</td>
<td>3.3</td>
<td>12.5&lt;sup&gt;26&lt;/sup&gt;</td>
<td>8125</td>
</tr>
<tr>
<td>PbO</td>
<td>318</td>
<td>12&lt;sup&gt;33&lt;/sup&gt;</td>
<td>12.9</td>
<td>3&lt;sup&gt;2&lt;/sup&gt;</td>
<td>954</td>
</tr>
<tr>
<td>CdSe</td>
<td>261</td>
<td>10&lt;sup&gt;14&lt;/sup&gt;</td>
<td>13.1</td>
<td>10&lt;sup&gt;21&lt;/sup&gt;</td>
<td>2610</td>
</tr>
<tr>
<td>CdTe</td>
<td>200</td>
<td>10.2&lt;sup&gt;24&lt;/sup&gt;</td>
<td>17.4</td>
<td>2.5&lt;sup&gt;17&lt;/sup&gt;</td>
<td>500</td>
</tr>
<tr>
<td>CdZnTe</td>
<td>206</td>
<td>10.1</td>
<td>16.7</td>
<td>0.25-0.5&lt;sup&gt;35&lt;/sup&gt;</td>
<td>51-103</td>
</tr>
<tr>
<td>TlBr</td>
<td>180</td>
<td>31&lt;sup&gt;29&lt;/sup&gt;</td>
<td>58.8</td>
<td>1&lt;sup&gt;31&lt;/sup&gt;</td>
<td>180</td>
</tr>
</tbody>
</table>

* Porous layer, a solid layer has $\varepsilon_r$=26.

Table 1. Possible x-ray photoconductors along with photoconductor thickness required for 75 % absorption at 90 kVp ($d_{75}$), dielectric constant ($\varepsilon_r$), capacitance of a 9" diameter (410 cm²) layer with a thickness of $d_{75}$ ($C_{75}$), typical photoconductor electric field ($E_{typical}$) and the voltage required for a layer of thickness $d_{75}$ ($V_{75}$).

The capacitance of the 9" vidicon $a$-Se layer is 3.3 nF, which is a little higher than that of a 1" Saticon or 1" Plumbicon, but is lower than that of a 1" Chalnicon (CdSe thickness<sup>22</sup> = 2 μm, As₂Se₃ thickness =
0.4 μm, A = −3 cm², C = −12 nF). Lag from this layer should be about 3% (See Chapter 3) when a diode gun is used. The other photoconductors have much higher capacitances and will therefore have higher beam discharge lag under the same signal conditions. The larger capacitance of these layers, which has the effect of increasing lag, is partially offset by the increased signal that is expected, which has the effect of decreasing the relative lag. The capacitance of the layers could be reduced by making them much thicker than \(d_{75}\) but this requires very long carrier ranges. An alternative solution used in the organic photoconductors of photocopy machines is to use separate layers for carrier creation and carrier transport. For example a thin TiBr layer could provide efficient absorption and carrier creation while an overlying organic photoconductor or α-Se layer would provide carrier transport and low capacitance. The potential required across a layer of thickness \(d_{75}\) for optimum sensitivity is given in Table 1 as \(V_{TS}\). Since most photoconductors have a value of \(V_{TS}\) that exceeds 100V they will probably require some method of preventing crossover in the form of a suppressor mesh or special surface coating. A low value of \(V_{TS}\) is in conflict with a low value of \(C_{75}\), therefore an x-ray sensitive photoconductor suitable for real time fluoroscopy (low lag) with \(V_{TS}\) <100V is unlikely.

Until another photoconductor can be found that meets the stringent requirements imposed by an x-ray vidicon it seems that α-Se is currently the best choice.

C. REDUCING NOISE

In Chapter 2, it was explained how noise could be minimized by keeping target stray capacitance low and by matching the capacitance of the preamplifier. Some alternate methods of reducing noise are eliminating the suppressor mesh, segmenting the target and GaAs transistors.

The suppressor mesh was added to the x-ray vidicon to allow stable operation with high target potentials. A significant reduction in stray capacitance could be achieved, however, by elimination of this mesh. This would be possible if the secondary electron emission of the target surface could be reduced to less than one secondary electron per primary at all incident energies. Such an inherently stable target will therefore require the development of an appropriate surface layer. (See Chapter 4).

The stray capacitance of the target can be effectively reduced by dividing the target into many individual target electrodes. Each of these individual electrodes is connected to its own preamplifier with each preamplifier seeing a much smaller capacitance than the full target would present. With 10 segments the
preamplifier input capacitance is reduced by $=10$ and the amplifier noise reduced by $(10)^{1/2}$ over the full target design. In effect each preamplifier sees the same input capacitance as a 1" vidicon.

In the segmented electrode technique individual preamplifier outputs need to be sequentially switched to the main video amplifier in synchrony with the beam scanning. This can present a problem with respect to line artifacts appearing in the image. These artifacts could occur as the result of one of the following:

1. spaces between electrodes
2. preamplifier switching that is not well synchronized with beam scanning
3. differences in gain between preamplifiers

By far the majority of vidicon preamplifiers use a Si JFET transistor at their input for its low noise properties. Recently, however, suitable GaAs FET transistors\textsuperscript{36,37} have become available. The GaAs FET has lower noise at high frequencies but has more low frequency noise. The existence of quantum noise makes low frequency amplifier noise less important in the x-ray vidicon than in a light sensitive vidicon (See Chapter 2). High frequency noise, however, is more troublesome in the large area vidicon due to the higher capacitance and GaAs FETS may provide an advantage.

D. RETURN BEAM READOUT

In a normal vidicon the signal current is taken from the target electrode and amplified directly by a preamplifier. An alternative to this mode of operation is to detect and amplify modulations which occur in the beam that returns from the target back into the tube (see Figure 1). In the dark the scanning electron beam does not deposit electrons on the target and the full beam current is reflected back into the return beam. If the target has been discharged by light or x-rays then the current required to recharge to target will reduce the return beam current. The advantage of using the return beam is that it can be amplified in an electron multiplier to provide a large signal current before leaving the tube. The disadvantage is that the signal current from the return beam vidicon is inverted with respect to the normal vidicon, that is maximum signal from the return beam vidicon indicates black.

The advantage of a return beam readout is that stray capacitance of the target is not a concern and transistor preamplifier noise is negligible. The dominant noise source in the return beam readout is the shot noise of the return beam which along with the signal is amplified relatively noise free by the electron multiplier to be well above transistor preamplifier noise. A disadvantage of return beam readout is the complexity of the tube with its associated electron multiplier structure.
Figure 1. Return beam readout.
Return beam readout originates from a photoemissive camera tube known as an Image Orthicon\(^{38}\). Light sensitive vidicons which incorporate the return beam structure of the image orthicon have been reported by Schade\(^{39}\) and Isozaki\(^{40}\). The return beam vidicon of Schade was 4.5" in diameter with an Sb\(_2\)S\(_3\) photoconductor while the tube of Isozaki was 2" in diameter with an a-Se target. Most image orthicons and return beam vidicons use a solenoidal magnetic coil for focusing which surrounds the entire tube. This coil could become cumbersome for larger diameter tubes. However, Miyashiro and Shirouzu\(^{41}\) have reported an image orthicon which is electrostatically focused and eliminates the need for a bulky solenoidal focus coil.

The fact that shot noise of the beam in the light sensitive return beam vidicon is present even in the dark, along with the added complexity of the tube has limited its application. Wiemer\(^{42}\) has produced a novel photoemissive return beam readout tube called the Isocon which does not have the problem of shot noise in the dark. No reports of "Isocon type" vidicons have been made in the literature probably due to their increased complexity over the "Orthicon type".

In a return beam vidicon the shot noise of the beam is minimized by limiting the beam current to a value just high enough to handle the highest signals. A quantum noise limited system can be maintained if the shot noise of the beam is less than the x-ray quantum noise at the lowest exposure rate of interest (usually 1/10th of the average exposure rate). In general, the return beam readout is best suited to applications involving low signals such as low dose GI fluoroscopy or high bandwidths such as 30 fps readout with >1000 lines. An analysis of the advantages of return beam readout versus normal readout is provided by Engstrom and Sternberg\(^{43}\) and also by Isozaki\(^{40}\). The analysis can applied to the x-ray vidicon by including x-ray quantum noise.

Overall, if a normal x-ray vidicon can be made which is quantum noise limited within the operating parameters of interest then a return beam readout offers no advantage. For large bandwidths or very low exposure rates, however, the return beam readout can offer quantum noise limited operation where the normal vidicon cannot.

### E. REDUCING TUBE LENGTH

The large area x-ray vidicon described in this thesis has approximately the same length as an XRII/TV combination of the same diameter. If the vidicon tube length could be reduced, however, it would make the device more manoeuvrable and lighter. When the length of the vidicon is reduced, the deflection
angle of the beam must be made larger, which makes perpendicular landing more difficult, and increases deflection defocussing. The extent to which the vidicon can be shortened will require modelling and testing. A radical method of reducing tube length is to introduce the electron beam from the side and deflect it sharply by 90° just above the target surface. This technique has been used by Aiken\textsuperscript{44} and Gabor et al\textsuperscript{45} to produce flat cathode ray tubes. The flat CRT concept of Aiken is shown in Figure 2. It involves a set of ~10 deflection strips which are sequenced appropriately to provide a smooth continuous scan of the electron beam. It may be possible to use this method to produce a flat, large area vidicon with a depth of 4" or less.

II. CONCLUSIONS

The large area x-ray vidicon has only a single conversion stage between the x-ray image and the electronic video signal. This single conversion occurs in a photoconductor which maintains high resolution by pulling charge carriers created in the bulk, along a straight path to the surface. These factors give the large area x-ray vidicon a distinct advantage over the present XRII/TV system which has multiple conversion stages and light scattering within its phosphors. The most important advantage is an improvement in the visualization of small objects of low contrast, (ie. improved MTF). In addition, the x-ray vidicon should be easier to manufacture and have a lower cost.

Attempts have been made in the past to produce a large area vidicon for medical fluoroscopy, however, they were unsuccessful. The problem was that the photoconductor was either of poor quality or short life or else it was not used with enough bias potential or a proper readout method. Since those early attempts, the photoconductor a-Se has undergone tremendous improvements for use in the commercially successful x-ray imaging system known as Xeroradiography. This system and its associated a-Se plates have demonstrated high quality x-ray images. These a-Se plates are therefore an excellent choice for the photoconductor of the large area x-ray vidicon.

For maximum sensitivity, these plates require an electric field of $10^7$ V/m. Calculations have shown that at this field along with typical fluoroscopic exposure rates, the x-ray vidicon can produce the same level of signal current on its target as the target of a similar XRII/TV system. Measurements of signal current made on a 6" demountable vidicon are in agreement with this calculation. Electronic noise in the x-ray vidicon will be larger than an equal size XRII/TV system (about 3x larger for 9" diameter). This is due to the larger target and thus larger stray capacitance seen by the preamplifier of the x-ray vidicon. Fortunately, the electronic noise of the x-ray vidicon although larger than that of the XRII/TV is still
Figure 2. The flat CRT of Aiken.
below x-ray quantum noise when considering typical fluoroscopic exposure rates and resolutions. Measurements of electronic noise made on the 6" prototype are in agreement with theoretical calculations for the capacitance of the target used. An analysis of signal to noise ratio versus spatial frequency has shown that the greatest advantage of the x-ray vidicon occurs in high resolution situations such as the 4.5" zoom mode of cardiac cine. In this situation, the x-ray vidicon has a larger modulation transfer for high spatial frequencies when compared to the XRII/TV and therefore has larger high frequency signals and signal to noise ratio. Structural noise in the XRII limits any boosting of the XRII/TV MTF in clinical practice. The x-ray vidicon, in comparison, has a negligible amount of structural noise.

To a first approximation the large area vidicon is a scaled up version of the 1" light sensitive vidicon used in the XRII/TV system. As such, the large area vidicon has the same relative modulation transfer as the 1" vidicon. The x-ray vidicon will therefore have a superior MTF when compared to an XRII and 1" vidicon combination. The improvement is more pronounced in zoom modes where the XRII MTF falls well below that of the 1" vidicon referenced to the x-ray input.

Calculations on the electron optics of the large area vidicon have been done to show that effects such as space charge repulsion, beam bending, spherical aberration and deflection defocussing are within acceptable limits. To reduce the bulk of the device the preferred electron-optical design is an electrostatic or magnetic focus electron gun located in a neck at the rear of the tube. The preferred deflection method is a magnetic yoke due to its smaller deflection defocussing compared to electrostatic deflection.

Beam discharge lag in the large area vidicon is roughly the same as that of the XRII/TV system. This is because the large area vidicon a-Se photoconductor has ~100x the area and ~100x the thickness of a 1" a-Se vidicon and thus equal layer capacitance. Photoconductive lag in the a-Se large area vidicon is expected to be small since the density of the bulk traps in xeroradiographic a-Se layers is known to be low. Preliminary observations of x-ray images on the prototype vidicon confirm that lag is small.

Two major problems were encountered when adapting xeroradiographic a-Se plates for use in a large area vidicon. The first problem was that the large potential (>1000V) needed to bias the a-Se layer can lead to an instability in surface potential when used in a vidicon. This instability, caused by excessive secondary electron emission, causes positive surface charging instead of negative. This problem was solved by incorporating a suppressor mesh in front of the target, and a coating of porous Sb$_2$S$_3$ onto the target surface to control secondary electrons. Tests in the 6" demountable vidicon showed that stable operation was possible with target potentials in excess of 3000V. Without the porous Sb$_2$S$_3$, the
Suppressor mesh potential must be lowered, which degrades resolution. While the suppressor mesh has been used in other types of television cameras, we believe that this is the first time it has been used in a vidicon.

The second problem is related to the polarity of the potential across the layer. Xeroradiographic plates are normally charged with a positive surface potential while the vidicon must necessarily charge the surface negatively. When charged negatively, xeroradiographic plates exhibit very high dark current. Three methods were tested in an effort to modify the a-Se blocking layers to reduce dark current. The most successful method, called inversion, involves the removal of the existing substrate metal and application of a new metal layer on the opposite side. Vidicon targets made by this process were tested in the demountable vidicon and showed low dark current (<20 nA) for bias fields up to 10 V/μm. In addition to producing a suitable target, these experiments support the theory that the dominant blocking action is due to trapping at the a-Se surfaces.

The fluoroscopic procedures which can most benefit from improved MTF and flexible zoom and panning modes are diagnostic cardiac angiography and interventional fluoroscopic procedures such as coronary balloon angioplasty. These procedures play a leading role in the detection and treatment of coronary artery disease, the leading cause of death in North America. The improved MTF offered by an x-ray vidicon could aid in the detection and evaluation of narrow internal vessel structures such as the eccentric slit-like stenosis and the intimal flap. The need for improved MTF in cardiac fluoroscopy is indicated by the frequent use of XRII/TV zoom modes. The zoom mode of an x-ray vidicon has a rectangular field of view which provides a larger viewing area when compared to an equal height circular image of an XRII/TV system. Another advantage of an x-ray vidicon is an ability to pan the zoom mode field of view within the full field of view. This would eliminate the present need to move the patient or imaging device while following the contrast as it passes from the top to the bottom of the heart. Placement of the zoom field of view at the edge of the full field of view would also allow the x-ray vidicon to be placed closer to the heart during angulated views to reduce focal spot unsharpness.

The XRII/TV system has been in use for approximately 40 years and has become a mature technology. While our prototype has not yet demonstrated image quality superior to the XRII/TV, it has demonstrated that the major problems facing the large area vidicon are soluble and has verified those theoretical predictions tested. It is expected that a second improved prototype will provide high quality images and fully demonstrate the advantages of a large area vidicon over the XRII/TV system.
REFERENCES


28. R. F. Butler (private communication)


