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MODIFICATIONS OF THE X-RAY SOURCE AND MONITOR AT THE X-RAY CALIBRATION FACILITY

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ABSTRACT

In order to test the instruments aboard the Advanced X-Ray Astrophysics Facility (AXAF) some modifications will need to be made in the X-Ray Calibration Facility at Marshall. Several of these modifications involve the x-ray source and the monitor. It is these modifications which are the subject of this report.

The source is redesigned to increase the spectral purity of the beam and decrease its polarization by minimizing the number of bremsstrahlung photons in the beam. This is accomplished by utilizing an annular electron gun designed by Dr. Jerry Gaines which allows us to take off the beam antiparallel to the direction at which electrons are incident on the anode. Two other features of the source are the conical anode which decreases the effective spot size and a rotatable anode and filter wheel which allows the operator to change targets without breaking vacuum.

The monitor is an important part of the facility because it is used to determine the x-ray flux at the target. A commercially available solid-state detector, Si(Li), should be used along with appropriate proportional counters for monitoring. This detector will be particularly useful when energy or wavelength dispersive instruments are tested because of its good resolution.

ACKNOWLEDGEMENTS

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Mr. H.R. Coldwater, Mr. J.H. Newton, and Mr. W.E. Dickson welcomed me warmly to Test Laboratory and had me feeling like I belonged within a week. My summer colleague, Mr. Cary Reily, deserves special thanks. He and his family really opened up their hearts to the Newbolts and we will never forget it. Cary spent much time with me discussing the modifications of the x-ray source and monitor, how the facility operates to test x-ray instruments, and several other matters of great and small importance in spite of a very heavy load of x-ray testing.

The day-to-day work of the calibration facility is in the hands of Mr. John McDougal, Mr. Barry Hale, Mr. David Watson, and Mr. David Javins. They have been helpful to me in every way. Thanks are also due to Mrs. Pat Blackmon who typed this report.

Finally, I would like to thank Enna Mae and Elizabeth, my wife and daughter, who spent the summer keeping house in a cramped apartment so that I could participate in the program. I am so glad that they were able and willing to join me in Huntsville this summer. Great going girls!

I. REDESIGN OF THE X-RAY SOURCE

The wording of my research task is fairly explicit about the source requirements. The first requirement is to increase the spectral purity of the beam. I have interpreted this to mean that there is a requirement to minimize the bremsstrahlung component of the spectra. An x-ray generator which minimizes the bremsstrahlung will also minimize the polarization of the beam since it is the bremsstrahlung which is partially polarized. The characteristic x-rays are unpolarized.

One way to minimize the bremsstrahlung is to take the x-ray beam out of the source antiparallel to the velocity of the electron before it encountered an atom and produced a photon. The simplest model of bremsstrahlung production from which we can extract any useful information suggests that a high energy electron encounters the atomic charge distribution and starts it ringing so that the atom has a time-dependent dipole moment.

$$\vec{P} = \vec{P}_0 \cos \omega t$$

The dipole oscillations are antiparallel to the electron's initial velocity and have an amplitude, $\vec{P}_0$. The parameter ω is the circular frequency of the dipole oscillations. See Figure 1. The average power radiated per unit solid angle at an angle 0 with respect to the oscillations and with respect to the electron's initial velocity is given by the formula

$$\text{Power Radiated per Unit Solid Angle} = \frac{c\, k^4 P_0^2 \sin^2\theta}{32\pi^2 \epsilon_0} \qquad 1$$

We notice that the power radiated is proportional to the square of the sine θ, which vanishes at zero degrees and 180 degrees.

Of course, many of the electrons will undergo scattering in the target so we cannot reduce the bremsstrahlung spectrum to nothing, but we should be able to minimize it with an x-ray tube that takes off the x-ray antiparallel to the electron's impact velocity on the target.

When I first started looking at cylindrically symmetric x-ray tubes, I was thinking of an annular, indirectly-heated cathode some distance from the anode and tilted 30° with respect to it. See Figure 2. This tube has some advantages in that the electrons do not need to be bent through large angles to reach the anode and it is possible to solve the

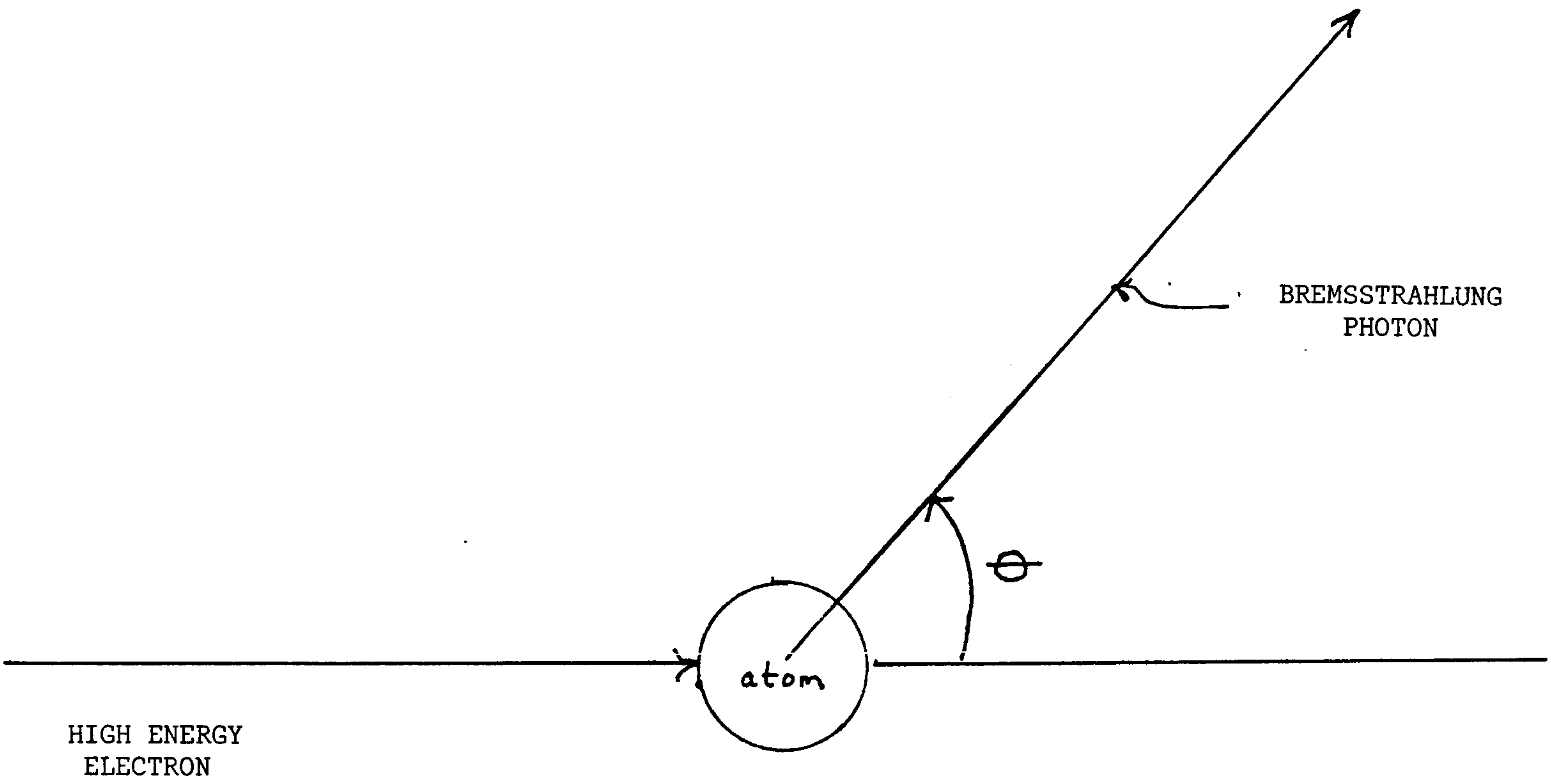

FIGURE 1
GEOMETRY OF BREMSSTRAHLUNG EMISSION

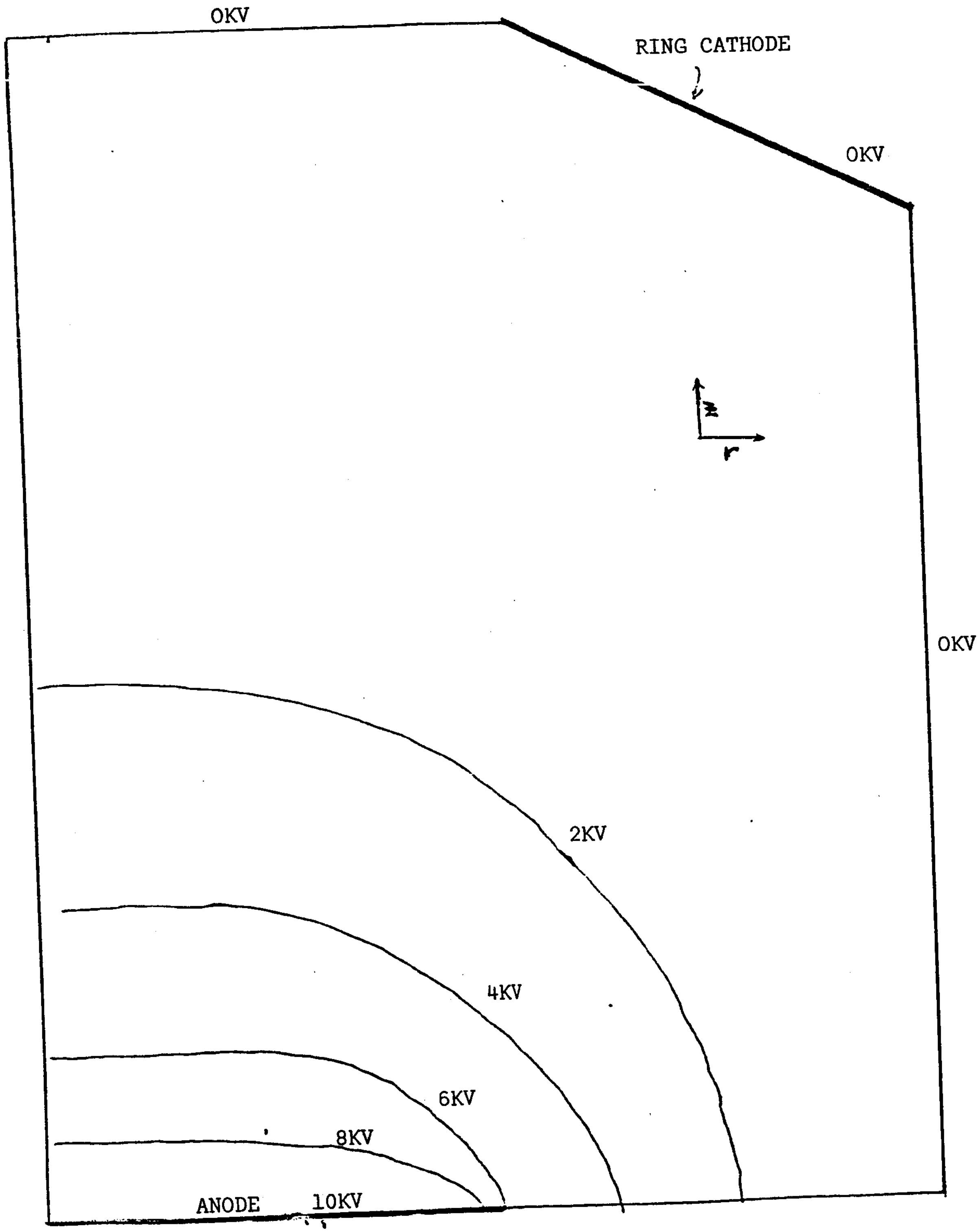

FIGURE 2
CYLINDRICALLY SYMMETRIC X-RAY TUBE

equations describing the field approximately. If we make the anode 10 KV positive with respect to the cathode and case, the equipotential surfaces will be approximately as shown in the figure. Electrons will track the field lines from the heated cathode where they are emitted. The field lines are everywhere perpendicular to the equipotentials. The determination of the equipotentials shown in the figure by an approximate solution of Laplace's Equation is described in the Appendix.

An x-ray tube designed this way will generate x-rays, but has several disadvantages: 1) the wide cathode makes it difficult to focus the electrons onto a small spot; 2) the tube cannot be operated easily with the anode grounded and the cathode negative because electrons will move to other grounded parts of the tube; and 3) it is necessary to break the vacuum of the source when another x-ray line is desired. For these reasons I began to look for another design which would 1) allow for a narrow cathode and a focusing electrode which would focus the electrons from a narrow ring cathode, 2) have an electron gun arrangement which would get the electrons started in the right direction before they wander off from the path to the grounded anode, and 3) have an anode-filter wheel so that a number of x-ray lines could be available without breaking the source vacuum.

As I became aware of the shortcomings of the simple x-ray tube, I received reprints of two papers by Dr. Jerry Lee Gaines [2,3] who developed an x-ray source for use in plasma diagnostics. He stated that the purity of characteristic x-ray lines in a source is greatly enhanced if there is no line-of-right path between anode and cathode. This inhibits sputtering or evaporation of one electrode material onto the other electrode.

The x-ray generator which I would recommend for use in the X-Ray Calibration Facility is shown, at least conceptually, in Figure 3. It is patterned after Dr. Gaines tube which seems to offer the best chance of meeting the requirements at the X-Ray Calibration Facility. This generator is not patented and is not available commercially. Dr. Gaines told me on the telephone that there is a company called Spectra-Mat which could fabricate the dispenser cathodes used in the electron gun. [4]

Unfortunately the electrostatics of this source is too complicated for the simple relaxation program described in the Appendix to be very helpful because: 1) the geometry is not cylindrically symmetric, and 2) and the electrons follow the overall field lines only approximately. We could approximate the fields and potentials by taking only the electron gun and anode, but this will not give us the electron trajectories because the full interplay of field and particle momentum is involved. Dr. Herrmannsfeldt [5] at Stanford Linear Accelerator Laboratory has written a computer program to establish electron trajectories in an electromagnetic field. Dr. Gaines has used this program to design his x-ray gun. I have tried to obtain a copy of the newest version of this program without success. If the program can be obtained, it may be possible to check and see if a ring focusing electrode is necessary near the anode to achieve a .5 mm spot.

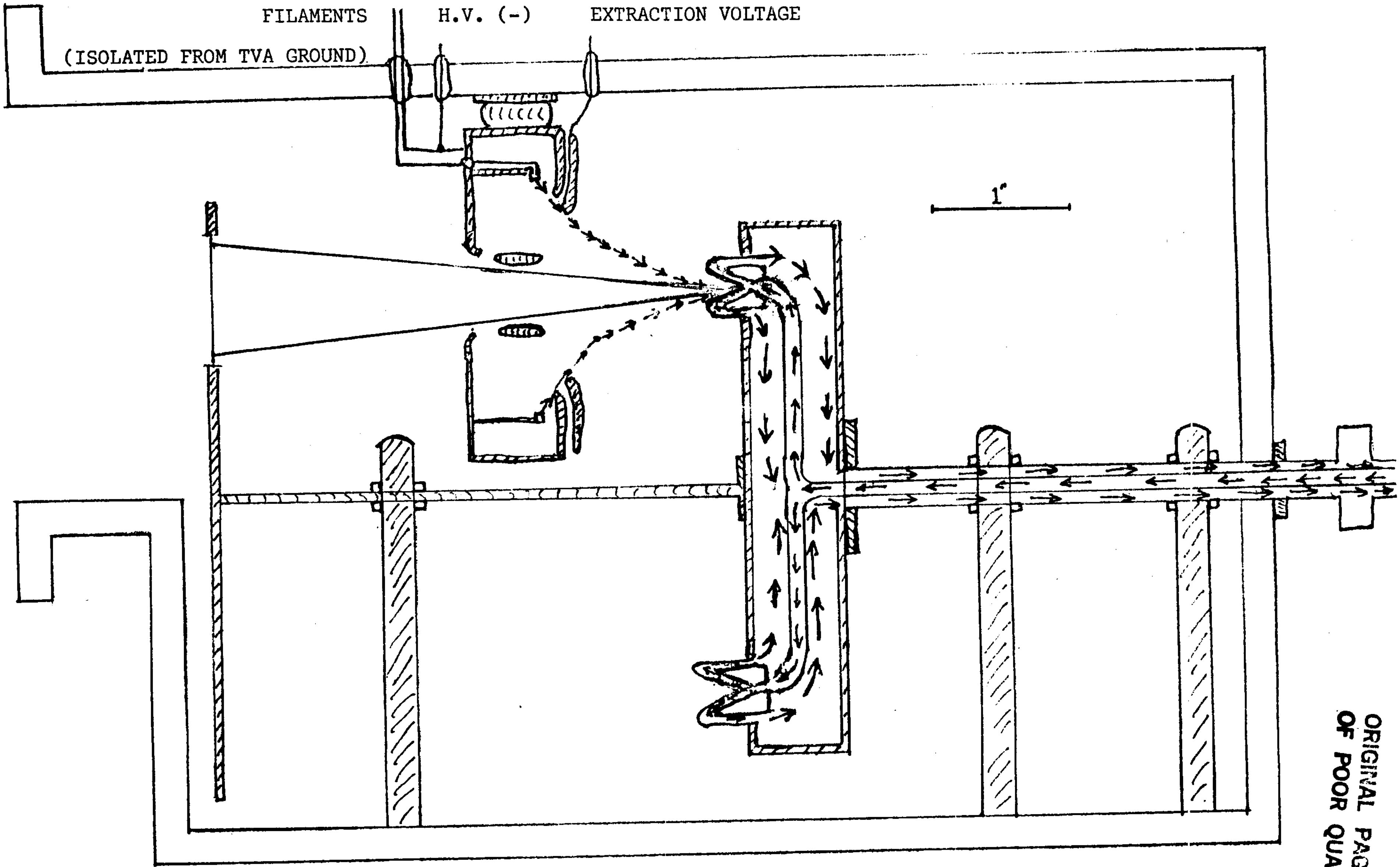

FIGURE 3

X-RAY GENERATOR

The x-ray generator I recommend is the design of Gaines with the following modifications: 1) the ring cathode is narrowed from 1.5 mm in width to .25 mm to make it easier to focus a small spot, and 2) the generator is contained in a compact cylindrical envelope with an off-center flange which can be attached to the x-ray flight tube. The conical shape of the anode is designed to spread out the heat generation over a large area but keep the projected spot size small.

The anodes and cooling manifold are mounted on an axle which also holds a filter wheel. Target and filter are selected by rotating this assembly by hand or by a stepping motor on a gear drive. The only vacuum seal is around this cooling pipe. Bremsstrahlung would be greatly minimized if we could make the target cones from Be-metal and evaporate or electroplate target materials onto them. The reason for this is that we would like to let the degraded electrons which have traversed enough material that they can no longer produce characteristic x-rays go into some low-Z material which does not produce many bremsstrahlung photons. The bremsstrahlung probability goes as the square of the atomic number.

I am uncertain about the best way to mount targets on the cooling manifold. For best cooling we would have them mounted directly over the cooling jets in the manifold but this means that there will need to be a vacuum seal for each one to keep cooling water out of the vacuum. It may be satisfactory to use metal conduction to the water and keep the cooling manifold sealed. For best heat conduction I suggest that the metal heat path should be Cu, Brass, or Al. I believe that stainless steel is a poor conductor of heat.

With these modifications the cathode can emit at least 50 mA without damage. It should be possible to design the cooling system to take away several kilowatts. Dr. Gaines says big conical targets can take 6 kilowatts without damage.

In the specifications for testing AXAF it is stated that 10^3 photons/cm^2-sec will be required. From Gaines' data on a version of the tube we can estimate the voltage necessary to achieve that flux with 50 mA emission current and his electroplated targets. The estimates are made with the formula of Green and Cosolett.[6] See Table 1.

TARGET ELEMENT	ENERGY (keV)	ANODE POTENTIAL FOR 10^3 PHOTONS/ CM^2-SEC AT 50 mA (K.V.)	FLUX AT 30 keV AND 50 mA (PHOTONS/CM^2-SEC)
Cu	8.047	16.6	4.7×10^3
Co	6.930	24.9	1.5×10^3
Mn	5.898	18.4	2.9×10^3
V	4.952	15.1	4.4×10^3
Sc	4.090-L	15.4	3.9×10^3
Ag	2.984-L	12.1	5.9×10^3
Zr	2.042-L	16.1	3.1×10^3
Al	1.487-L	11.8	5.3×10^3

TABLE 1

ESTIMATES OF ANODE POTENTIALS
REQUIRED TO REACH 10^3 PHOTONS/CM^2-SEC

II. MODIFICATIONS OF THE X-RAY MONITOR

The present proportional counter has functioned as a reliable and trouble-free monitor. Two difficulties with the monitor might be discussed here: 1) counting gases must be handled in the vacuum behind very thin windows which must be supported on some kind of mesh, and 2) the relatively poor resolution of the detector means that we are integrating over a lot of noise in the multichannel analyzer.

One way to alleviate some of these difficulties would be to choose a solid-state detector as a monitor. I hoped to find a solid-state detector which could be used as a monitor and function at ambient temperature. This would mean that only electrical lines would have to go into the vacuum (signal and bias connections). A lot of research has gone into the development of mercuric iodide crystals as photon detectors. [7] Although they have good resolution and operate at room temperature, they have disadvantages. The yield of good detectors from the crystalline material is low and it is difficult to characterize the material which will produce good detectors. If it is desired to investigate mercuric iodide crystals further, it is possible to obtain some experimental detectors from E.G.&G., Santa Barbara Operations. Dr. Rolf Woldseth [8] at Kevex advises that in an operation where it is important that the operating characteristics remain constant a lithium-drifted silicon detector is the best choice. Unfortunately, mercuric iodide crystals age quickly. That is, their resolution degrades as a function of the total photon energy they have detected.

With this sobering advice I began to consider use of a lithium-drifted silicon detector as the main x-ray monitor. The attractive features of these detectors are their excellent resolution and reasonable detection efficiency over the AXAF range of energies. The only problem arises between 0.1 keV and 0.5 keV where few photon detectors are very efficient. Unfortunately silicon detectors take up water, atmospheric gases, and other substances with which they come in contact. If they are to be operated in the windowless mode, they must be protected with a gate valve. Otherwise they are supplied with thin Be windows to prevent contamination of the silicon. The thinest window supplied by E.E.&G. for their detectors is 0.3 mils of Be [9]. With this window the efficiency of the detector is down to 5% at 0.5 keV; the windowless detector is down to 5% at 0.3 keV. On the positive side the efficiency is over 80% between 2 keV and 12 keV and there are no steep edges to interpolate over.

When the detector is put in service, rough efficiency curves will be supplied by the manufacturer, but you will need to calibrate it carefully over the AXAF range. The best method would be to find some radioactive source standard which does not emit beta particles which might be detected in the device, like Am^{241}. The National Bureau of Standards can supply essentially point sources of standard activity. For other radioactive nuclides there is a fixed ratio of the x-ray line due to internal conversion, and the gamma line. If, for example, the gamma ray line is in the region where the efficiency is 100%, the measurement of the line profiles will give the efficiency for the x-ray line directly. These lithium-drifted silicon detectors are not useful beyond 100 keV in energy.

III. TEST RIG FOR GENERATOR AND MONITOR

In the near future modifications of the X-Ray Calibration Facility will begin. It is important that the design and testing of the generator and monitor proceed in parallel with the heavy construction on the tube and pumping system. It would be useful to build a rig for testing generator designs, the monitor, and the uniformity of the flux. I envision a stainless steel tube which can be evacuated, the x-ray tube or standard photon source mounted on one end, and the detector [Si(Li)] mounted behind an aperture and positioned by an (x,y) positioner.

It would be helpful if the rig were designed so that the anode spot could be viewed with a pin-hole camera. This would allow the focus and spot size of the generator to be determined as a function of the operating parameters of the source. These measurements will determine whether another focusing electrode is needed in the generator.

Most of the difficulties that may arise with the generator and monitor (anode spot too large, flux inhomogeneity, and difficulty calibrating the monitor) should be apparent from measurements made on the test rig. If these difficulties are dealt with at the test rig before the heavy construction is completed, it should be possible to install the generator and monitor without serious complications.

RECOMMENDATIONS

An x-ray tube patterned after the tube designed by Dr. Jerry Gaines should be considered for the x-ray generator. The following modifications will need to be made in the design: 1) the dispenser-cathode will need to be made narrower, and 2) a water-cooled manifold to hold a number of targets and a filter wheel should be mounted in the x-ray source so that different targets may be rotated into the electron beam without breaking the vacuum.

A lithium-drifted silicon detector should be considered for the x-ray monitor. Its excellent resolution and reasonable efficiency over the AXAF range of energies make it a likely candidate. Although mercuric iodide crystals appear to have attractive properties, they are probably still too experimental for consideration. The detector will need to be calibrated with known photon sources, and perhaps in some ranges by the x-ray to gamma ray method.

It would be helpful if a small-scale test facility could be used to test generator and monitor designs before these items are installed at the modified facility. The test facility should provide flux surveys of the x-ray beam, imaging of the focal spot on a piece of x-ray film, and testing and calibration of a lithium-drifted silicon detector as a candidate for monitor.

APPENDIX

The electrostatics of regions of space bounded by conductors held at fixed potentials by external circuits is determined by Laplace's Equation. If we work in a cylindrically symmetric coordinate system and call the coordinates (ρ, θ, z), we can write the equation as

$$\frac{\partial^2\phi}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial\phi}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial^2\phi}{\partial\theta^2} + \frac{\partial^2\phi}{\partial z^2} = 0$$

where ϕ is the electrostatic potential. In the case of our simple tube there is rotational symmetry about the axis of the tube so that the equation becomes

$$\frac{\partial^2\phi}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial\phi}{\partial\rho} + \frac{\partial^2\phi}{\partial z^2} = 0$$

If we set up a net in the (ρ, z) coordinate space, we can write a set of numerical operator which will approximate the derivatives. The net has a regular spacing , and I and J are indices specifying the points of the net. They begin at one and end at the boundaries. See Figure 4.

$$\rho = (I-1)h \quad \text{and} \quad z = (J-1)h$$

$$\frac{\partial^2\phi}{\partial z^2} \doteq \frac{\phi(I,J+1) - 2\phi(I,J) + \phi(I,J-1)}{h^2}$$

$$\frac{1}{\rho}\frac{\partial\phi}{\partial\rho} \doteq \frac{\phi(I+1,J) - \phi(I-1,J)}{(I-1)h \qquad (2h)}$$

$$\frac{\partial^2\phi}{\partial\rho^2} \doteq \frac{\phi(I+1,J) - 2\phi(I,J) + \phi(I-1,J)}{h^2}$$

Substitution of these operators in Laplace's Equation establishes an important result; the potential at a point of the net is a weighted average of the potential at neighboring points of the grid, and the weight factors are determined by the coordinate system.

$$\phi(I,J) = \frac{\phi(I,J+1) + \phi(I,J-1) + \left[1 + \frac{1}{2(I-1)}\right]\phi(I+1,J) + \left[1 - \frac{1}{2(I-1)}\right]\phi(I-1,J)}{4}$$

This relationship may be used to calculate the fields of cylindrically symmetric region where the boundary potentials are known. The method is called the method of relaxation, and we move across the net with the computer repeatedly setting the potential at each point equal to the appropriate weighted average of its neighbors until the process converges. This is the method which was used to determine the potentials in Figure 1.

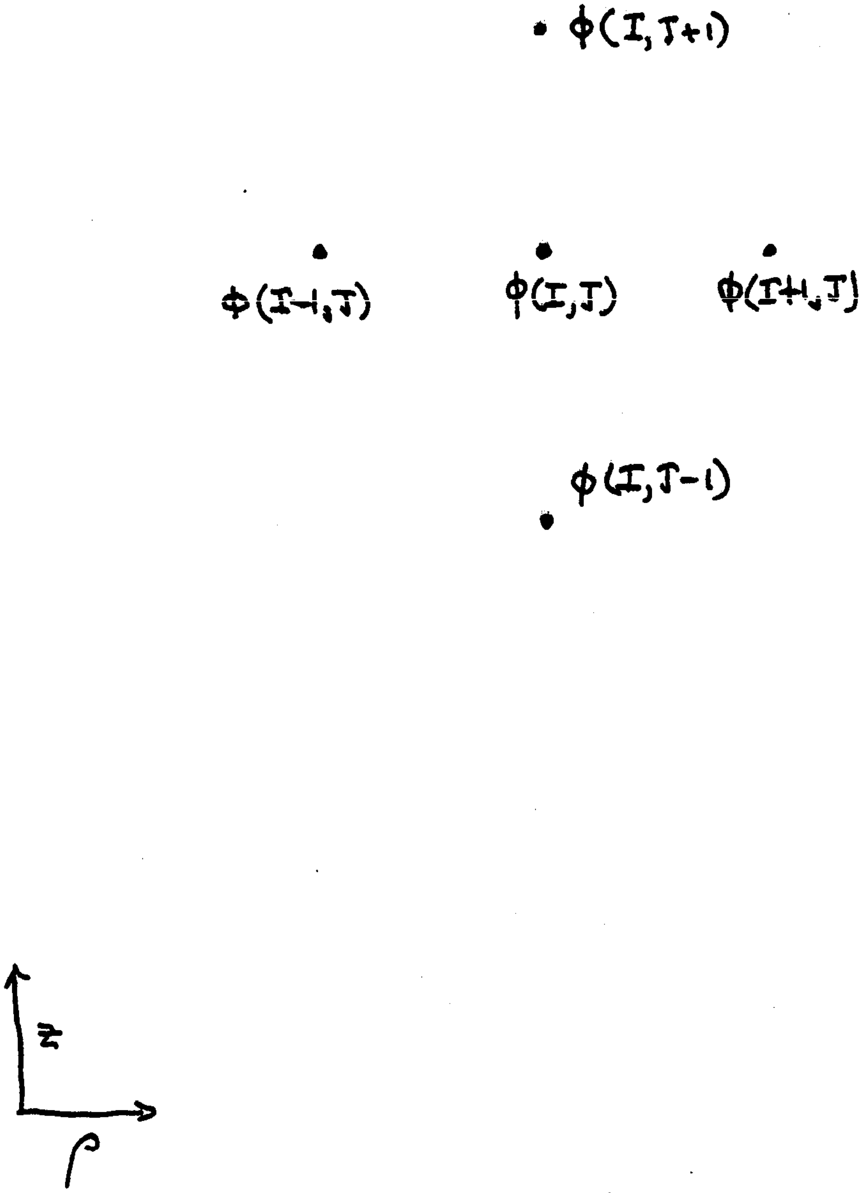

FIGURE 4
NET FOR SOLUTION OF LAPLACE'S EQUATION

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