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Sandia Mark II X-Ray System

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Sandia Laboratories

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SANDIA MARK 11 X-RAY SYSTEM

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ABSTRACT

The Sandia Mark 11 X-Ray System was designed and developed to provide an intense source of monenergetic, ultra-soft x-rays with energies between 0.282 and 1.486 keV. The x-ray tube design is similar to one developed by B. L. Henke and incorporates modifications made by Tom Ellsberry. An operations manual section is incorporated to help the experimenter/operator.

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ACKNOWLEDGMENT

The author expresses his gratitude to K. M. Glibert of Experiments Planning Division 1112 for his scientific advice and assistance, and to Tom Ellsberry of J-14 Division, Los Alamos Scientific Laboratory for his expert technical advice during the design and construction of this system.

WARNING

THE MARK II X-RAY SYSTEM AND ITS ASSOCIATED
HIGH-VOLTAGE POWER SUPPLY DEVELOPS LETHAL
VOLTAGE AND CURRENT.

IT IS EXTREMELY IMPORTANT THAT THE OPERATOR/
EXPERIMENTER READ THE OPERATING INSTRUCTIONS
SECTION (APPENDIXES A AND B) OF THIS REPORT
BEFORE USING THE MARK II X-RAY SYSTEM.

CONTENTS

	<u>Page</u>
Introduction	9
System Components and Design	10
High-Voltage Power Supply	10
Differential Voltmeter	13
Emission Controller and Cathode Power Supply	13
X-Ray Tube Design	15
X-Ray Tube Water Cooling System	21
Water High-Voltage Separator	23
Vacuum System	23
Anodes	28
Conclusion	28
References	29
APPENDIX A -- Vacuum System Operating Instructions	31
APPENDIX B -- X-Ray System Operating Instructions	35

ILLUSTRATIONS

Figure

1	System Schematic (Mark II)	11
2	High-Voltage Power Supply	11
3	Control Rack	14
4	X-Ray Tube	16
5	Anodes	18
6	X-Ray Tube Focusing	19
7	X-Ray Tube Chamber	20
8	Water Cooling System	22
9	Water High-Voltage Separator	24
10	Anode High-Voltage Water System	24
11	Vacuum System Schematic	25
12	Vacuum Pumps	26

SANDIA MARK 11 X-RAY SYSTEM

Introduction

The Sandia Mark 11, a high-intensity ultra-low energy, x-ray system has been designed and developed to calibrate x-ray detectors, and to measure the areal density of elemental foil materials. Among other uses, we can also calibrate x-ray film used in our crystal spectrographs and in grazing-incidence spectrometer/spectrograph systems and to determine dead-layer thicknesses of silicon (Si) PIN detectors.

The x-ray tube used in this system is patterned after the design of H. L. Henke at the University of Hawaii,¹ but includes modifications made by the Los Alamos Scientific Laboratory (LASL) to enhance the x-ray output.²

The system has unique properties that provide several advantages:

- With the interchangeable anode design, we can generate and observe directly, using a variety of anode materials, the characteristic radiation previously generated with secondary fluorescer techniques, thus obtaining higher fluences with less power
- We eliminate manufacturing difficulties previously encountered in the tube base assembly of x-ray systems; these difficulties have been described by Morrison and Clibert³
- We can produce approximately monoenergetic photon spectra over the energy range of from 0.282 to 1.486 keV
- We can easily adapt this machine to different types of experimental setups that require ultra-low energy x-rays

In this report, system components are described and an operations section included, but particular emphasis is placed on the unique design of the tube.

System Components and Design

The similarity between the Sandia Mark II and the Sandia Henke x-ray systems³ was deliberately planned. Most components of both systems are interchangeable saving stock room for spares.

Figure 1 is a schematic of the electrical portion of the system. Individual components will be discussed in their own sections. These components include the high voltage power supply, the differential voltmeter, the emission controller and cathode power supply, and the x-ray tube design. The high-voltage water cooling system and the water high-voltage separator are discussed in their own sections as is the vacuum system.

High-Voltage Power Supply

The power supply in the Mark II X-Ray System (Figure 2) supplies positive high voltage to the anode of the x-ray tube. It is a standard, commercially available unit with a few specified factory modifications, manufactured by Universal Voltronics Corp., and is designated Model BRE-5-1000-S. The "S" in the number indicates that a 400- Ω resistor has been added in series with the high-voltage output to protect the unit in case there is a high-voltage arc in the x-ray tube during operation. Another addition is a built-in voltage-dividing network that supplies power to a digital voltmeter and recorder. This unit can also be converted into a source of negative high voltage by reversing a factory-wired plate inside the rear door of the unit and moving the PLUS/MINUS switch on the front panel to the MINUS position.

The regulator-control circuit must be cooled because the large vacuum tubes generate large quantities of heat. A "muffin" fan is mounted on the door at the rear of the rack and the draft directed around the circuit/tube assembly and out the top of the rack.

Figure 1. System Schematic (Mark II)

Figure 2. High-Voltage Power Supply

The electrical specifications of the power supply are as follows:

- Input: 190 to 230 V ac, 60 Hz
8.0 kVA (approximate)
- Output: 500 to 5000 V dc, 1000 mA
- Polarity: reversible
- Ripple: less than 0.01% rms
- Regulation, load-to-line: 0.1% over the entire voltage range from no load to full load

Components that are designed to protect the total system and maintenance personnel are as follows:

- Time-delay interlock relay: Allows a 15-s delay for the tube filaments to warm up
- External interlock: Assures that enough cooling water is flowing through the x-ray tube housing and anode
- Primary circuit breaker interlock: Controls power to the regulator circuits
- High-voltage access interlock: Indicates that all high-voltage access panels are in place
- Overload-overflow: Meter relays that insure that voltage and current are not exceeded
- Set range interlock: Assures that all high-voltage selector switches are in ZERO position

Care must be exercised during repairs. The interlock circuit in the access door turns off all power to the rack, but some circuits may remain charged with LETHAL VOLTAGES when the rack door is open.⁴ A high-voltage shorting stick attached to the rack door must be used to discharge the high-voltage circuits to water pipe ground before attempting any circuit repairs.

Differential Voltmeter

The anode potential is one of several factors that controls the shape of the x-ray spectrum emitted from the Mark II system. Since the spectrum must be reproduced to calibrate the detectors, it is imperative to monitor and control the anode potential. This voltage is measured with a John Fluke Model 891A differential voltmeter (Figure 3) across a voltage divider in the high-voltage power supply; this divider was designed specifically for measuring differential (null) voltage. The voltmeter can measure positive or negative voltage and has a full 20-kV dc range. The signal across the sensing resistors is directly proportional to the output voltage.

To establish the desired voltage for the anode, set the selected value on the voltmeter and adjust the high voltage until it nulls the meter. As the tube current increases, some loading of the power supply occurs and the voltage must be adjusted to null the meter.

When the system is operating, any change in the output of the power supply is detected and can be corrected to maintain constant potential to the anode. The voltmeter can detect variations as small as 0.01%.

Emission Controller and Cathode Power Supply

The emission controller designed by LASL regulates the electron emission of the cathode, thereby regulating the x-ray output of the system (Figure 3). The controller is connected to the cathode-anode circuit and controls--and displays--the amount of thermionic emission that is transferred from the cathode to the anode. The emission controller draws power to heat the cathode from a Hewlett-Packard Model 6264B programmable dc power supply.

$$Q_{\text{out}} = Q_{\text{in}} + Q_{\text{H}_2\text{O}} + Q_{\text{H}_2}$$

Fig. 2. Control system.

The control system was constructed with the SIMULINK block diagram computer program and the control of the emission controller was reduced to the solution of a number of the above-mentioned transfer functions and the calculation of the control signals. The system controller parameters were determined from the requirements for the transient and steady-state

the signal for the other half comes from the x-ray tube in the form of thermionic emission current. Any change in the setting of the potentiometer will change the reference current through the resistors, thus the power supplied to the cathode and thermionic emission current of the tube. The emission controller will increase or decrease the power automatically until its null condition is satisfied.

The controls on the front panel of the emission controller are:

- MONITOR DEMAND MULTIPLIER switch - 0.1 to 1000
- DEMAND-CURRENT potentiometer - 0 to 100
- Manual - automatic switch
 - Manual position overrides the null condition of the x-ray tube emission controller and is controlled directly by the voltage and current potentiometers on the cathode power supply.
 - Automatic mode; see above.
- ON-OFF switch and light
- Fuses; line and output
- Meter and thermionic emission current monitor

The maximum output of the cathode power supply is 24 V, 100 mA, with a load regulation of <0.01% change in voltage and <0.01% change in current; this is equal to the voltage and current rating of the cathode. The voltage-current stability is <0.01% total drift for 8 hours at 25°C ambient conditions following a 30-min warmup.

The emission controller varies the cathode power to the tube in the remote programming mode of the supply.

X-Ray Tube Design

The x-ray tube for this system is similar to those described by Honke¹ and L. Ellsberry² which were designed specifically to produce intense, ultra-soft, x-ray spectra. Figure 4 shows the x-ray tube with

the water-cooled tube chamber removed, displaying the internal components of the anode assembly. Each component is identified in the figure.

Figure 4. X-Ray Tube

The tube was designed for low-energy photon production and the following important factors that enhance the output and maintain rather intense and pure spectra entered into the design considerations:

- Anode power
- Anode cooling
- Anode surface contamination
- Space charge effects
- Vacuum window thickness
- Anode voltage
- Removable anode

When compared to that of conventional tubes, the x-ray production efficiency of the Mark II is much less because of the low voltage that is required to minimize bremsstrahlung background. Therefore, to obtain an intense radiation source, the anode is operated at high anode currents. High anode currents require that the anode be cooled. The anode is hollow and water circulates through it during operation, preventing the tube components from melting (Figure 5).

Anode contamination cannot be allowed if pure characteristic x-ray spectra are to be generated. Since low-voltage excitation is used for the system, the accelerating electrons do not have the energy to penetrate the anode much beyond its surface, so most of the x-ray production occurs at the anode face. Consequently, the spectra will be characteristic of the material at the surface rather than in the interior of the anode. This characteristic radiation is superimposed on a bremsstrahlung spectrum.

Tungsten and carbon were the two most important forms of anode contamination considered when designing this tube. Tungsten vapor is produced when electrons are thermionically emitted from the helical tungsten cathode, and carbon contamination results when low vapor pressure carbonaceous compounds (such as pump oil) are deposited on the anode.

In conventional x-ray tubes the filament is directly opposite the anode and the tungsten vapor is easily deposited on the anode. To eliminate this problem, the helical tungsten filament was placed behind and hidden from the electron impact area of the anode and the vaporized tungsten is deposited on the backside of anode holder away from the chamber window, on an area not used to produce x-rays.

Figure 5. Anodes

To reduce carbon contamination, the anode temperature is kept between several hundred degrees centigrade and the melting point of the anode material. Also when the tube vacuum is first roughed out, the air is evacuated with Vac Sorb[®] pumps operated on liquid nitrogen. The pressure is further lowered and maintained at least at 1.33×10^{-6} Pa (10^{-6} torr) with an Aired[®] turbomolecular pump. The Vac Sorb pumps are then valved out.

The thermionic emission is electrostatically focused so that the electrons strike the anode along its apex, just opposite the tube chamber window (Figure 6). Electrostatic focusing is provided by the field lines created by the anode/cathode geometry and by the tube chamber. A metal strip directly behind the cathode supplies additional focusing.

The focusing strip, tube chamber, and cathode support post are at ground potential. With this configuration, space charge can suppress the anode current, thereby limiting x-ray output, so a set of flaps was added to the rear of the anode holder, partially surrounding the cathode. These flaps reduce space charge around the cathode.

Figure 6. X-Ray Tube Focusing

A thin exit window is necessary to maintain a hard vacuum (1.33×10^{-4} Pa) on the anode side. The photons produced at the anode must be able to exit the tube chamber with little attenuation. This design uses a window made of 160 micrograms/cm² of carbon that is coated with 1500 Å of aluminum; this window hardly attenuates ultra-soft x-rays. The thin window can be damaged and may fail if elastically scattered electrons were to interact or strike it. If it failed, the vacuum in the tube would fall, resulting in substantial damage to the tube and to the vacuum system. Operating the anode with a positive high voltage eliminates elastically scattered electrons and the other tube components can be grounded, lessening the high-voltage danger for the operator. The operator is also protected by the plexiglas shield that covers the coolant and high-voltage cables leading from the table top to the x-ray tube flange (Figure 7).

Figure 7. X-Ray Tube Chamber

The Sark II can also be operated without the window if

- A vacuum of $>1.5 \times 10^{-4}$ Pa is maintained at the anode
- Visible light from the tungsten filament is not harmful to the attached experiment

Output is enhanced by placing the irradiated portion of the anode as close as possible to the window opening in order to maximize the solid angle subtended by the emerging beam.

X-Ray Tube Water Cooling System

Since the cathode/anode assembly produces heat in the tube chamber, the anode and the chamber must be cooled to prevent damage to the internal tube components. Tap water circulating through the anode and through the chamber jacket accomplishes this purpose.

Figure 8 shows how the water cools the anode and the tube chamber. Incoming water pressure is regulated to 310 kPa (45 psig) and the water is filtered before entering.

Its temperature is monitored with a sensor in the main water line (H_2O temperature readout, Figure 3). After passing through the pressure regulator, filter, and flow meter, the flow of water is divided into two branches: one cooling the anode and the other the chamber jacket.

The flow meter regulates the amount of water which determines the operating temperature of the anode and the chamber. The meter indicates the flow rate in gallons per minute and is coupled to an interlock system that closes when the flow rate in the meter rises above a preset value. The interlock system also supplies the signal that activates the external interlock circuit of the high voltage power supply. Anode outlet water temperature is monitored with a sensor (Figure 3) before it enters the building drain system.

The following specifications are important to properly operate the Mark II:

- Inlet pressure: 310 kPa (45 psig)
- Incoming water temperature: 15° to 27°C (60° to 80 F)
- Chamber/anode flow rate: $1.26 \times 10^{-4} \text{ m}^3/\text{s}$ (>2 gal/min)

Figure 8. Water Cooling System

Water High-Voltage Separator

High voltage is applied to the anode of the x-ray tube through a high-voltage cable (Figure 9). The water high-voltage separator (which is in the anode cooling water circuit) is attached to the high-voltage anode electrical circuit (Figure 10) and isolates the high voltage from the ground reference of normal tap water by acting as a large resistor. The separator uses the inherent resistance of the water which is about $1 \text{ M}\Omega$ from the anode (positive high voltage) to ground (cold water pipe). The separator consists of a plastic box (which also serves as a personnel electrical shield) with two continuous lengths of polyethylene tubing, each one 9.5-mm (3/8-in) inside diameter and 6.1 m (20 ft) long. The incoming cooling water travels through one length of tubing, enters and cools the anode through the high-voltage probe, and exits through the second tube into the building drain.

Since loss of water flow between the regulator and the anode could cause the tube to overheat the transparent plastic box allows any problem inside the water separator to be quickly noticed and corrected by the operator.

Vacuum System

The design criteria for the Mark II Vacuum system were

- Quick-reacting (<10 min) pumps; atmosphere to $1.33 \times 10^{-4} \text{ Pa}$ (10^{-6} torr)
- No oil vapors leaking from the pump to the tube chamber
- Reliability and serviceability

The Mark II vacuum subsystem uses two Varian Vac Sorb pumps and one Airco turbomolecular pump (Figures 11 and 12).

Figure 9. Water/High-Voltage Separator

Figure 10. Anode High-Voltage Water System

The Vac Sorb pumps may be operated in tandem or independently to rough down the tube chamber to approximately 0.67 Pa (5×10^{-3} torr). The pumping speed, as quoted by the manufacturer for the volume to be evacuated in the Mark II, is about 10 min. Actually, after the pumps are chilled with liquid nitrogen, it takes only 2 to 3 min to evacuate from atmosphere to around 0.67 Pa.

Figure 11. Vacuum System Schematic

Figure 12. Vacuum Pumps

When the Vac Sorb pumps are operated independently, the pumping speed can be described by the formulas

$$C = 12Aw \text{ (L/s/cm}^2\text{)}$$

and

$$\frac{1}{S_{eff}} = \frac{1}{S_{pump}} + \frac{1}{C}$$

where

C = conductance through the port, in litres per second

A = area of port, in centimetres squared

W = transmission probability

S_{eff} = effective system pumping speed

S_{pump} = pump speed for air

Since the port area is 11.96 cm² (4.71 in²),

$$C = (12 \text{ L/s/cm}^2)(11.96 \text{ cm}^2)(0.2) = 21.7 \text{ L/s} .$$

The Airco turbomolecular pump is mechanically attached to the bottom of the tube chamber and has a manufacturer-quoted pumping speed of 500 L/s. It is capable of evacuating to the required 1.33×10^{-4} Pa. The port area of this pump is larger than that of the Vac Sorb pumps and the calculated pumping speed is 35.7 L/s.

This speed is adequate for normal operating. Since the pump rotates at 24 000 rpm (1.44×10^6 rps), water must be used to cool the impeller bearings. The incoming water pressure for the pump is controlled to 310 kPa (45 psig) by a regulator and is filtered before entering the bearings. The amount of water required to cool the bearings adequately is specified by the manufacturer as 2.1×10^{-5} m³/s (0.33 gal/min). The water flow rate is monitored by a meter above the high voltage power supply cabinet. The meter housing contains a switch which closes when the preset flow rate is reached. This switch sends a signal to the water flow interlock circuit of the turbo pump control unit. The turbo pump cooling water exits the pump and enters the building drain system.

The vacuum is monitored with thermocouple and ion gages. The readouts are on meters on the Model 843 Vac Ion^(TM) gage controller (Figure 3).

Anodes

Elemental materials were used to manufacture anodes for the Mark II System. Specifications for materials require an elemental purity of 99.99%. During manufacturing, no foreign materials, such as oil, are used.

The elemental anode materials presently available and their characteristic x-ray energies are

Beryllium (Be) - 0.110 keV

Boron (B) - 0.185 keV

Carbon (C) - 0.282 keV

Oxygen (Al_2O_3) - 0.523 keV
(anodized)

Titanium (Ti) - 0.530 keV

Copper (Cu) - 1.100 keV

Magnesium (Mg) - 1.254 keV

Aluminum (Al) - 1.486 keV

The monoenergetic x-ray spectra obtained with this machine from these materials will be reported later. We anticipate the spectral purity in most cases to exceed 90%. The experimental equipment for measuring the spectral purity will be a windowless silicon detector, a crystal spectrometer, a xenon ion chamber, and a flow proportional counter.

Conclusion

The recently designed Sandia Mark II helps the researcher calibrate x-ray detectors and film, measure the areal density of foil materials, and determine the thicknesses of Si PIN detectors. With this new machine we can obtain higher fluences with less power than previously obtainable. We can also produce monoenergetic photon spectra from 0.282 to 1.486 keV. Not

only can it be used for different experiments, but its parts are also interchangeable with those of the Henke x-ray system, thereby saving money and stock room₇.

References

¹Burton L. Henke, Advances in X-Ray Analysis, Vol 13 of An Introduction to Low Energy X-Ray and Electron Analysis (New York: Plenum Press, 1969).

²Tom Ellsberry to Author (Los Alamos: J-14 Division, Los Alamos Scientific Laboratory, 1977). Private communication.

³L. W. Morrison and K. M. Glibert, Henke X-Ray System. SAND74-0006 (Albuquerque: Sandia Laboratories, July 1974).

⁴Operations and Repair Manual for the Model No. BRE 5-1000-S Power Supply, (NP: Universal Voltronics Corp, nd).

APPENDIX A

Vacuum System Operating Instructions

1. Close valves 1, 2, 3, 4, and 6 in the Vac Sorb pump area (Figures 11 and 12).
2. Fill the Vac Sorb pump dewars with liquid nitrogen. Allow approximately 10 min for the pumps to start.
3. Fill the liquid nitrogen dewar of the Welch roughing pump. This reduces the oil back-streaming which might occur when the roughing pump is started.
4. Close the roughing pump bleed valve 7. Turn on the Welch roughing pump. This evacuates the exhaust side of the turbo pump. The roughing pump dewar has to be filled only once.
5. Turn on the thermocouple gage readout unit (Figure 3) by depressing the PWR button on the Model 843 Vac Ion gage controller. Monitor the vacuum on the TC1 meter at the right side of the panel.
6. Open valve 4, then slowly open one (either 1 or 2) of the valves at the top of the Vac Sorb pumps.
7. Observe the vacuum on the TC1 meter. When it reaches 13.3 Pa (100 mtorr), slowly open the high vacuum shutoff valve (5) located between the turbo pump and the tube chamber. The thermocouple gage reading will move upscale but should recover to 13.3 Pa in a few minutes.
8. Open the other Vac Sorb pump valve. The vacuum should decrease to from 0.13 to 1.3 Pa (1 to 10 mtorr); when reached, proceed to the next step.

9. Turn on the H_2O power switch. Observe the water flow meters above the high voltage power supply and press the H_2O START pushbutton switch. The meters will indicate water flow to the turbo pump as well as to the x-ray tube anode and chamber jacket. The water flow relays behind the H_2O switch panel will remain latched when enough cooling water is flowing through the system.
10. Check the TC2 meter that indicates the turbo pump exhaust pressure. The pressure reading must be less than 6.5 Pa (50 mtorr) before you proceed to the next step.
11. Airco Turbomolecular Pump System (Figure 3).
 - 11.1 Meaning of Indicator Lights on the Airco SSC-150 SS Converter.
 - 11.1.1 A lit CONVERTER light: converter is operating normally. If the CONVERTER light does not go on, check the fuses on the rear panel.
 - 11.1.2 A lit ACCELERATE light: the pump motor is accelerating and the converter frequency has not yet reached the frequency set on the speed potentiometer, R1, on the rear panel.
 - 11.1.3 A lit RUN light: the pump motor has reached run speed and the converter frequency is equal to or greater than the set frequency.

NOTE

The ACCELERATE and RUN lights indicate only the mode in which the converter is operating, ie, whether it is in the ramp or has reached constant speed. Output status is indicated by the OVERLOAD light, which is not lit when converter output is normal.

11.1.4 A lit OVERLOAD light: output power has stopped for one of the following reasons:

1. The converter frequency has not risen above the preset level within 1.25 min. This happens if the pump operates at full atmospheric pressure or if a bearing fails.
2. The converter frequency has not reached the run setting within 12 min, which is the same as being at current limit for 12 min. This happens if a bearing fails during acceleration, or if there is a gross vacuum leak.
3. Output has risen above a factory-set limit. This is a converter fault. (See the troubleshooting section of the Airco SSC-150 SS Converter Manual).
4. The WATER contacts have opened. The WATER light is an interlock and indicates a gross drop in the flow of cooling water. The VACUUM and AUX1 Light interlocks are not used.

11.2 Turn On Procedures

When power is applied to the unit, the red light within the toggle switch on the front panel goes on. Turn the unit on by flipping this switch upward. The CONVERTER indicator will light up. The output frequency quickly rises to 100% as indicated by the RUN light and the frequency meter. Within the next 2 to 5 s, the output frequency falls to below 100 Hz, and then begins a gradual 8-min rise to its upper limit.

- 11.2.1 The vacuum indicated on the thermocouple gage readout (TC1) will drop when the turbo pump has attained a better vacuum than the Vac Sorb pump pressure

12. Close valve 4. The turbo pump pressure should decrease to about 0.13 Pa (1 mtorr) as indicated on the TCl meter.
13. Turn on the Vac Ion gage by pressing the ON button of the Model 843 Vac Ion gage controller. Monitor the pressure on the Vac Ion meter on the left side of the panel. The pressure should continue to decrease to the 10^{-4} Pa (10^{-6} torr) region.
14. Outgas the Vac Ion gage tube by pressing the DEGAS button on the Model 843 Vac Ion controller. The pressure will increase rapidly, then decrease slowly to approximately 10^{-4} Pa (10^{-6} torr). The DEGAS button does not have to be pressed for more than 5 min; longer periods of outgas may damage the Vac Ion tube.

APPENDIX B
X-Ray System Operating Instructions

Turn On Procedures

1. The tube chamber vacuum should be around 10^{-4} Pa (10^{-6} torr). Turn on the MAIN, PRIMARY, and CONTROL switches on the center right portion of the high voltage power supply (Figure 2). The MAIN POWER light (green) and the cabinet cooling blowers will come on.
2. Turn on the John Fluke differential voltmeter (Figure 3). After a 15 to 30 s delay, the delay relay in the power supply will be energized and the HV ON switch may be engaged to supply high voltage to the anode.

WARNING

The high voltage in this system is LETHAL. The high voltage/water separator and the tubular plexiglas wire/hose shield on the table top are designed to protect the operator from these high voltages.

3. Increase the high voltage to the desired accelerating potential, which is approximately three times the energy of the x-ray line of interest.
4. When the desired high voltage shows on the power supply meter, check the differential voltmeter settings to be sure that the high-voltage settings are approximately correct.
5. Turn on the Emission Controller (Figure 3). The control mode switch should be on AUTOMATIC.

6. Turn on cathode power supply
7. Move the COARSE current and voltage potentiometers on the cathode power supply to the 3 o'clock position.
8. Adjust the DEMAND CURRENT potentiometer and the MONITOR DEMAND decade switch on the emission controller to the desired tube emission current, using the following equation:

$$\begin{aligned} & (\text{tube emission current}) \times (\text{accelerating high voltage}) \\ & = \text{x-ray tube power in watts} \end{aligned}$$

Tube power should never exceed 3 kW and the temperature change (ΔT) of the anode cooling water, as indicated by the difference between the input and output digital temperature indicators located to the left of the differential voltmeter, should never exceed 11°C (20 F).

9. When the tube emission current (indicated by the emission controller meter) has become stable, adjust the accelerating high voltage to the desired value.
10. Observing the differential voltmeter, adjust the high voltage power supply dials until a null point on the differential voltmeter is reached. The system is now fully operational and is emitting x-rays.

Shut Down Procedures

1. Turn the DEMAND CURRENT knob to zero. The tube emission current will go to zero.
2. Reduce the accelerating high-voltage knobs to zero. The voltage meter will follow.
3. Press the HV OFF button.

4. Turn off the emission controller and the cathode power supply.
5. Turn off the MAIN, PRIMARY, and CONTROL power switches on the high voltage power supply.
6. Allow the water to remain on since the turbomolecular pump still needs coolant.

The x-ray emitting portion of the machine is now shut down.

Vacuum System Shut Down Procedures

WARNING

Never allow the turbomolecular pump to come up to atmospheric pressure abruptly. This pump rotates at 24 000 rpm (1.44×10^6 rps) and could be extensively damaged if allowed to rotate at atmospheric pressure.

1. Close the high vacuum SHUT OFF valve (5) located between the x-ray tube chamber and the turbo pump.
2. Turn off the Vac Ion gage tube by pressing the OFF switch (orange) on the Model 843 Vac Ion gage controller.
3. Turn off the turbo pump power by flipping the toggle switch downward. The pump will begin to slow down immediately and stop in about 30 min.
4. When the turbo pump stops, turn off the H₂O switch.
5. Slowly open the bleed valve (7) at the top of the Welch roughing pump until the pump gurgles.
6. Turn off the Welch roughing pump.

The x-ray tube chamber will retain some vacuum pressure. Possibility of contaminating the anode will be lessened if the vacuum in the tube chamber is allowed to exist during shutdown. The complete system is now shut down.

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