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DESIGN AND
CONSTRUCTION OF A
50 KILOVOLT X-RAY UNIT

Thesis for the Degree of M. S.
MICHIGAN STATE COLLEGE
Young Chang Kim
1951

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DESIGN AND CONSTRUCTION OF A
50 KILOVOLT X-RAY UNIT

by

Young Chang Kim

A Thesis

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Young C. Kim

TABLE OF CONTENTS

	PAGE
I. INTRODUCTION	1
II. DESIGN OF APPARATUS	2
a) High voltage supply	12
b) Rectification unit	12
c) X-ray filament circuit	14
d) Lead box and x-ray tube	15
e) Safety apparatus	15
f) Spectrometer	16
III. OPERATION AND TESTING OF APPARATUS	18
a) Operation	18
b) Testing and testing data	20
IV. CONCLUSION	26
V. REFERENCES	27

I. INTRODUCTION

This thesis reports the construction and testing of a 50 kilovolt x-ray unit and an associated Bragg spectrometer. It may be used for measurement of absorption edges and for taking Laue and powder pictures, and is quite suitable for general use in any x-ray experiment requiring an x-ray source of medium intensity at a voltage not higher than 50 kilovolts. Since it embodies a water cooled tube, it can also be used for experiments which require long exposure times.

The apparatus was constructed at low cost from surplus materials and other supplies available in the physics laboratory. This report gives a general description and a detailed discussion of the required voltage supplies and the safety devices necessary to protect personnel against high voltage and harmful radiation.

II. DESIGN OF APPARATUS

The main considerations in the design of the apparatus arise because of the restriction which the intended use of the apparatus places upon it. Since it was felt that it might be desirable to make measurements of a continuous x-ray spectrum, self-rectification could not be used. This implies the necessity of using some type of full wave rectifier. The ordinary kenetron capable of handling inverse voltages of 50 kilovolts or greater is large and rather expensive. To obviate this difficulty small Machlett rectifier diodes were used. Although these have a maximum inverse voltage rating of only 50 kilovolts, it was found possible to reach higher voltages by putting pairs of them in series. The Machlett rectifier is about 6 inches high with its anode consisting of a heavy copper base about 2 inches high sealed to the glass envelope. The filament current required for these tubes is about 20 amperes. In order to dissipate the large amount of heat developed by such a filament current, the rectifiers must be cooled by either water or forced air. In the present case it was impractical, because of the insulation problem, to cool the rectifiers by water. They were therefore mounted in a rectangular box through which a forced air flow was maintained by a small motor driven blower. To provide the large filament

current for the kentrans it was necessary to construct a filament transformer. In addition to the requirement that the filament transformer must be capable of delivering the correct current, it was necessary that it be capable of standing the full voltage applied to the x-ray tube itself. This restriction can be understood from the fact that the x-ray tube which was used employed a water cooled anode. The positive side of the power supply was therefore at ground potential, and the negative side at about 50 kilovolts below ground potential. The filament transformer consists of a rectangular yoke on which the primary is wound. The secondary is made in the form of a large circular coil and supported by glass tubes in such a way as to provide a large air separation between the primary and secondary. The transformer for the unit was a Kelly Koett type JA special 90. The transformer was formerly part of a medical unit, and therefore was normally used to supply current only over rather limited intervals of time. The transformer was designed to supply about 114 kilovolts with a primary 210 volts. Despite the fact that the transformer was designed for only the intermittent use, it has given satisfactory service for rectified voltages of 50 kilovolts or less over a rather long period of testing.

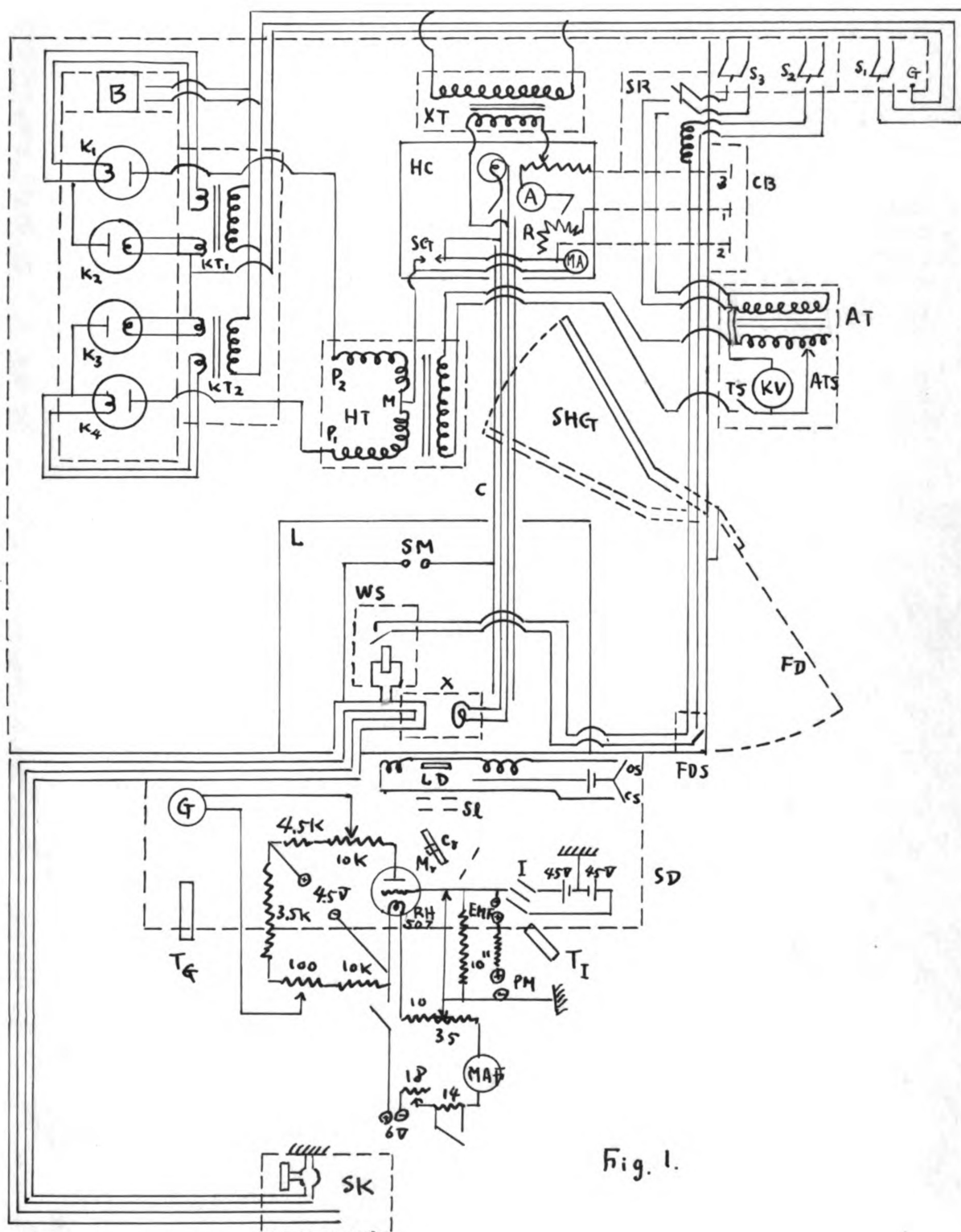
Another very important problem in designing any x-ray apparatus is the provision of proper safety devices

for the personnel who may operate the apparatus. These must protect personnel from radiation and prevent them from coming in contact with the high voltages. To accomplish the first objective the tube itself is mounted in a large lead box. The emitted beam is brought out through a lead tube which collimates the radiation fairly well. To eliminate the danger of high voltages, the entire high voltage system is mounted behind a wire cage. Access to this cage, is afforded by a door to which is fastened a shorting bar and small contactor. When the door is opened, the bar connects the high voltage terminal directly to ground. At the same time the circuit through the contactor is broken and the supply voltage is turned off. Two remaining details of the apparatus should be mentioned at this point. The first is the control circuit for the system. It consists essentially of an autotransformer in the primary of the high voltage transformer. This control circuit consisting of the autotransformer and controlling accessories are part of the original medical unit from which the high voltage transformer was taken.

The x-ray tube has a water cooled molybdenum anode. A pressure switch is provided in the relay circuit to the primary of the high voltage transformer, to protect the tube from having the beam turned on when the water is not flowing.

The design details discussed in this section are

shown in Figs. 1, 2, 3, 4, 5 and 6. Fig. 1 shows a schematic diagram of the wiring of the system with various elements of the system labeled in the attached list. Fig. 2 shows the wire cage containing the lead box with the controls for the system are at the lower right. Fig. 3 shows part of the control system for the x-ray tube filament, and the top of the high voltage transformer at the lower left. Fig. 4 and 5 shows the box containing the rectifiers. The secondary of the rectifier filament transformer is visible below the box. Fig. 6 shows the x-ray tube as it is mounted inside the lead box. The leads to the right are the water connection. In the lower right one can see the pressure switch.



Directory for Diagram

E.S.B.: Electric source switch board

S₁: Switch for 115 VAC source
S₂: Switch for 270 VAC source (2 ϕ) (for relay)
S₃: Switch for 270 VAC source (1 ϕ , grounded)

C.B.: Control board

1: Control rod for switch of x-ray filament circuit.
2: Control rod for major rheostadt of x-ray filament circuit.
3: Control rod for minor rheostadt of x-ray filament circuit.

A.T.: Auto transformer

A.T.S.: Auto transformer steps
K.V.: Kilovolt meter
T.S.: Transformer switch

S.R.: Relay for safety apparatus

S.H.G.: Static high voltage shortening bar
F.D.: Door of main cage
F.D.S.: Contactor switch of the door of main cage.

L.: Lead box

W.S.: Water pressure switch
X: X-ray tube
S.M.: spark meter
L.D.: Lead door for x-ray beam to spectrometer

O.S.: Switch to open the lead door
C.S.: switch to close the lead door
L.D.B.: Battery for lead door

K.T.: Transformer for Kenetron filaments

K.: Kenetron tubes
B.: Blower

X.T.: Transformer for x-ray filament

C.: High voltage cage

A.: Ammeter for filament current of x-ray tube
FS.: Switch for filament circuit of x-ray tube
R.: Major rheostadt in x-ray filament circuit
r.: Minor rheostadt in x-ray filament circuit
MA: Milliammeter for electron current of the x-ray tube
S.G.: Spark gap

H.T.: High voltage transformer

S.D.: Desk for spectrometer

Se: Slit for x-ray beam

Cr: Crystal (Calcite)

M: Mirror

I: Ionization Chamber

Ti: Telescope for Ionization Chamber

MAF: Milliammeter for triode filament

G: Galvanometer

Tg: Telescope for Galvanometer

E.M.F.: Terminals for Electromotive force

P.M.: Terminal for Potentiometer

Sk.: Sink for cooling water



Fig. 2

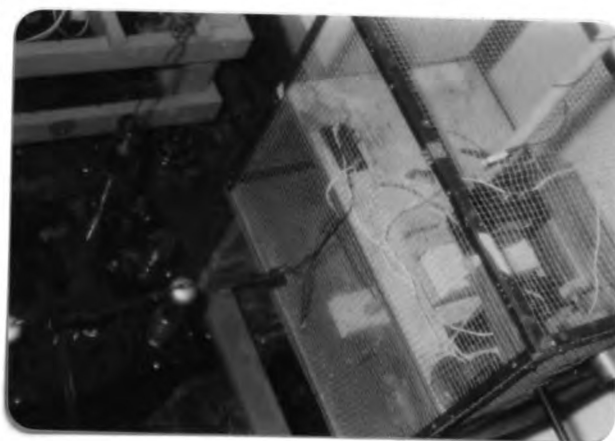


Fig. 3



Fig. 4



Fig. 5

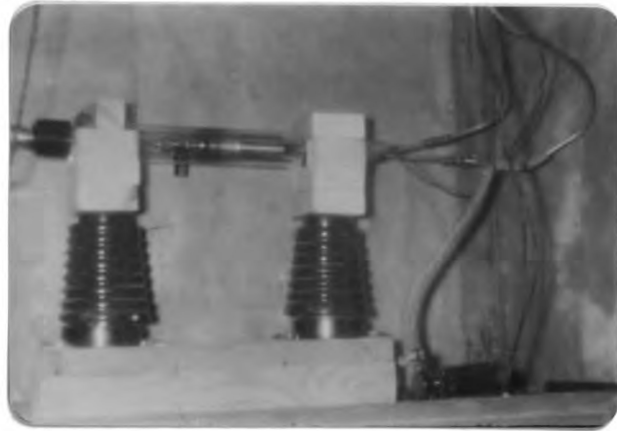


Fig. 6



Fig. 7

a) High voltage supply

The high voltage supply consists of a Kelly Koett type J A Special 90 high voltage transformer rated at 114 kilovolts and 725 milliamperes, which is supplied by a 230 volt A C source controlled through an auto transformer rated from 20 to 230 volts A C at 60 amperes. A kilovolt meter, calibrated for this high voltage transformer, is located in the auto transformer. A transformer along with an on-off switch on the panel board, control the high voltage supply which is taken from the center tap of the high voltage transformer.

b) Rectification unit

The four Machlett diodes*¹ are connected in two parallel sets, each set consisting of two tubes in series, thus giving full wave rectification. They are mounted on four elliptically shaped flat aluminum bases spaced at least 6 inches apart in a wooden box, 1½ by 1½ by 4½ foot with a blower which forces approximately 50 cubic feet of air per minute into one end of the box and out the other. The filaments are supplied from two sets of air-insulated step-down transformers, each with a single primary and two secondaries. Each primary is wound on

*¹Machlett VT 141 PI5 11.5 volts 20 amperes filament, plate (air 50 cubic feet/minute) 50 kilovolts.

the arms of a hollow square of laminated transformer iron approximately 1.3 feet in outside dimensions and with a 2 by 2 inches cross section. These are mounted vertically on a wooden frame. The secondaries are doughnut-shaped, $1\frac{1}{4}$ feet in diameter with two of them (for K_1 and K_4) supported vertically on glass tubes at right angles to and interlocking with their respective primaries. The other two secondaries (for K_2 and K_3), which are at ground potential, are supported obliquely on a bakelite rod but allowed to touch their respective primaries.

The data on the filament transformers are as follows:

Table 1

Data on filament transformers.

	<u>No. of winding</u>	<u>Wire Size</u>	<u>No load voltage</u>	<u>Full load voltage</u>
KT ₁ : primary	290	No. 14	120 V	120 V
secondary for K_1	47	No. 14	19.5 V	10.5 V
secondary for K_2	35	No. 10	14.5 V	10.5 V
KT ₂ : primary	265	No. 14	120 V	120 V
secondary for K_3	30	No. 10	13.5 V	10.5 V
secondary for K_4	40	No. 14	18.1 V	10.5 V

The current drain in each diode is about 19 amperes.

Differences in wire size, number of windings, and no load voltages arise because the primaries and secondaries for K_1 and K_4 were salvaged from an earlier x-ray unit and secondaries for K_2 and K_3 were wound to give the same

out-put voltage with the rectifying diodes in the circuit rather than to give similar impedance characteristics.

If all the filament windings had been wound in the same manner, the impedances would have been matched in each case.

The plates of K_1 and K_4 are connected to the secondary of the high voltage transformer. The output is taken from the center tap of that winding.

c) X-ray filament circuit

The x-ray filament circuit is connected to the negative side of the high voltage supply. This necessitates the housing of the x-ray filament supply and its control resistances in a wire cage (2.5 by 1.6 by 2 feet) made of 1/4 inch square wire net. This cage is connected to the secondary center tap of the high voltage transformer and is well insulated from ground by porcelain insulators. The x-ray filament transformer (XT) made by X-ray Corporation in Chicago sets on the floor under the cage. The secondary supplies 20 volts A C with no load, 6 volts A C 4 amperes with full load at a primary voltage of 120 volts. The x-ray tube filament has an impedance of less than 1.5 ohms for a 60 cycle A C source, so two variable resistances (the larger R 5 to 10 ohms, the smaller r 0 to 1 ohm) are inserted in series with a 6 ohm pilot lamp in parallel with x-ray tube filament. The leads from the high voltage cage to the x-ray tube filament in the lead box

go through a 1 inch conduit, which is connected to the high voltage cage and insulated by porcelain insulators from the lead box which is grounded. The x-ray filament circuit is connected to the cage through a milliammeter (MA) which shows the electron current through the x-ray tube.

d) Lead box and x-ray tube

The x-ray tube is mounted in a lead box (L), 3 by 3 by 4 feet, framed by 1/8 by 3 inches L section angle irons to which 1/8 inch lead plates are screwed. On the high voltage transformer side the entire wall of the lead box constitutes a door which opens to allow access to the inside. On the other side, at the center of wall of the lead box is a hole 1 by 2 inches with a lead door (LD) which may be closed and opened by an electromagnet which is activated by the switches (CS and C.S) and a battery (LDB). A water-pressure switch inside the box is connected to the return flow of the cooling water pipe. The x-ray tube has flat molybdenum target and is mounted as shown in Fig. 6.

e) Safety apparatus

The entire x-ray system except the control panel is enclosed in a wire cage, 9' x 9.25' x 7' high, made of one inch wire mesh and supported by a wooden frame work

of 2 x 4"s lumber. All conducting parts of this main cage are grounded. On one side is a door $7\frac{1}{2}$ feet wide.

A shorting bar is fastened on the top of the door (see Fig. 1) so that as it is opened this bar makes contact with the high voltage conduit. The bar is made of a steel rod 5 feet long and $5/8$ inch diameter, and bent as shown in Fig. 1 so that its end is 12 inches from the conduit when the door is closed and makes contact to the conduit with the least motion of the door when it is opened.

The contactor switch of the door (DS) and the water pressure switch (WS) are inserted in series in the circuit of relay (SR). If the door is opened by mistake the contactor switch opens the relay circuit and cuts off the main electric source for the auto-transformer. The water pressure switch (WS) insures the water cooling of the x-ray target in the same way.

f) Spectrometer

The spectrometer system is composed of three lead slits, a calcite crystal (Cr), an ionization chamber (I), a resistance bridge^{*2}, and a galvanometer (G). All of these are mounted on a rigid wooden table except the

^{*2}Leeds and Northrup Co. Serial number 324054, Catalog number 7673.

galvanometer which is set on a wooden board fastened to the frame of the main cage is shown in Fig. 7.

The telescope (T_g) is used with the galvanometer (G) and the telescope (T_i) is used with the ionization chamber (I). Once the reading of the telescope (T_i) is recorded when the x-ray beam is entering the ionization chamber, the same reading will always insure that the beam is entering the chamber. The preliminary calibration is made with the aid of a fluorescent screen. The reading is taken from the scale mounted on the top of the ionization chamber as reflected by a mirror rigidly mounted on the crystal holder. The electric connections of the electrometer tube circuit, galvanometer, and ionization chamber are shown in Fig. 1. Variable resistance No. 1 of the bridge is 10 kilohms and No. 2 is 100 ohms. The triode is a RH 508, and the variable filament resistance is 18 ohms and the bias resistance is 35 ohms. Since the filament current of the triode should be very steady, the filament current should be turned on several hours before the experiment begins. Further details will be discussed in the next section.

III OPERATION AND TESTING OF APPARATUS

a) Operation

We now discuss the operation of the various controls in the system. The method by which various controls function can best be explained by indicating the consecutive steps used to put the system into operation.

1. The flow of cooling water is increased until one hears the pressure switch inside the lead box close.
2. The magnetically operated shutter covering the port from the lead box housing the x-ray tube is closed by pressing the switch (CS).
3. The door to the large wire cage is closed. Care must be taken that the door is completely shut in order that the contactor switch mounted on the door frame closes.
4. Close the 115 VAC switch (S_1). This supplies the voltage for the filaments of the rectifier diodes, for the motor of the blower, and for the primary of the x-ray filament transformer (XT).
5. Close the x-ray filament switch. This switch is in the small wire cage within the larger cage. It is controlled by a small bakelite rod (1) running out through the side of large cage. The small pilot lamp indicates when the current is on. The current may be adjusted by rods (2 and 3).

6. Turn on the 270 VAC 3-phase switch (S_2). If the safety switches are closed one will hear the click as the relay switch closes.
7. Turn on the main switch (S_3) of 270 VAC 1-single phase. Then adjust this voltage by selecting the proper tap of the auto-transformer. A rough estimate of the cut put of the high voltage transformer can be obtained by the voltmeter on the panel board. This voltmeter is calibrated to read directly the secondary voltage of the high voltage transformer.
8. Turn on the transformer switch (TS), after one makes sure that relay switch on the control panel board is on.
9. To use the Bragg spectrometer, the filament current circuit of the triode RH508 should be turned on several hours before the experiment starts. Adjust the filament current to about 50 miloamperes with the aid of filament variable resistance (18 ohms) and the miliammeter (MAF).
10. Set the crystal (Cr) to the position of the largest angle of the range of angles which the experiment requires, with the aid of tangent screw.
11. Set the ionization chamber to such a position that the reflected x-rays hit the window of the ionization chamber, with the aid of telescope (Ti), mirror on crystal holder, and the scale on the top of the chamber.

12. Close the galvanometer circuit and balance the bridge with the aid of variable resistance No. 1 (10 kilo ohms) for rough adjustment and No. 2 (100 ohms) for fine adjustment.
13. After the galvanometer is settled down, read the scale with the aid of telescope (Tg).
14. Open the lead door (LD) with the aid of switch (OS).
15. Read the maximum deflection of the galvanometer.
16. Close the lead door (LD).
17. Change the angle of crystal and position of ionization chamber for next step.
18. After the galvanometer has settled down, read the scale of galvanometer and repeat the above process.

b) Testing and testing data

The calibrated spark gap meter (SM) was used to check roughly the reading of the kilovoltmeter (KV) with good agreement resulting in the range from 20 to 55 kilovolts. The electron current through the x-ray tube is variable in the range from 0 to 10 milliamperes. The testing data of continuous, characteristic, and absorption spectra are shown in Table 1 and 2 and Fig. 8 and 9. The calibration and calculation from these are as follows. The following calibration holds for a molybdenum target

with a silver absorber and a calcite crystal in the spectrometer. The wave lengths of the characteristic x-rays from molybdenum are $0.71 \text{ \AA}$ and $0.63 \text{ \AA}$ respectively, and the absorption limit by silver is $0.48448 \text{ \AA}$. The Bragg relation is $n\lambda = 2d \sin \theta$, where $d = 3.03560 \text{ \AA}$ for calcite, λ is wave length of x-ray beam, θ is the reflecting angle of crystal, and n is positive integer. And for small angle, $\sin \theta \approx \tan \theta = t/r$, where t is the tangent screw reading in millimeter and r is the distance from the tangent screw to the center of crystal rotation which is about 119 millimeter. If we let $100t = (x \angle x_0)$, then we get following results with the aid of Tables 1 and 2.

$$\lambda(\text{in } \text{\AA}) = (2d/r)t = (2d/100r) (x \angle x_0)$$

$$0.71 = 0.000511(1210 \angle x_0) \quad x_0 = 80^\circ$$

$$0.63 = 0.000511(1150 \angle x_0) \quad x_0 = 83^\circ$$

$$0.48448 = 0.000511(870 \angle x_0) \quad x_0 = 78^\circ$$

We take the average $x_0 = 80$.

From Fig. 9, the cut-off wave length is $\lambda = 0.000511(500 \angle 80) = 0.29638 \text{ \AA}$. Therefore the peak voltage is $12.378/0.29638 = 41.76 \text{ KV}$. This agrees approximately with the reading of kilovoltmeter (KV) which was 41.5 KV.

*³ Aproull: X-ray in practice

*⁴ Compton and Allison: X-ray in theory and experiment.

Fig. 10 shows the wave form of the rectified voltage - it is poor because adequate filtering could not be used.

Table 2

Data used in calibration of the instrument, target: Mo.
tube current: 7 mA, filament: 4.2 A, 41.5 KV.

x: Micrometer reading for calcite crystal angle

y: Galvanometer reading for intensity (Ti reads 6.1 on scale)

x	y	x	y
1700	2.3	1155	15.5
1650	2.5	1150	16.3
1600	2.7	1145	15.7
1550	2.9	1140	15.1
1500	3.0	1135	14.7
1450	3.2	1130	10.6
1400	3.4	1125	7.1
1375	6.2	1100	3.6
1350	19.6	1150	3.2
1325	37.2	1100	3.2
1320	37.7	950	3.1
1315	38.7	900	3.0
1310	39.5	850	2.5
1305	38.1	800	2.3
1300	37.3	750	2.1
1275	10.1	700	1.8
1250	4.7	650	1.4
1200	3.6	600	0.9
1175	6.5	550	0.5
1170	10.5		
1165	14.2		
1160	15.0		

Table 3

Data on absorption edges of Ag absorber Ag(90%) Pb(10%)
thickens 1/400 inch

x	y
1000	1.1
950	1.0
925	0.9
900	0.8
895	0.8
890	0.8
885	0.7
880	0.6
875	0.5
870	0.4
865	0.3
860	0.3
855	0.2
850	0.2
825	0.2
800	0.2
775	0.2
750	0.25

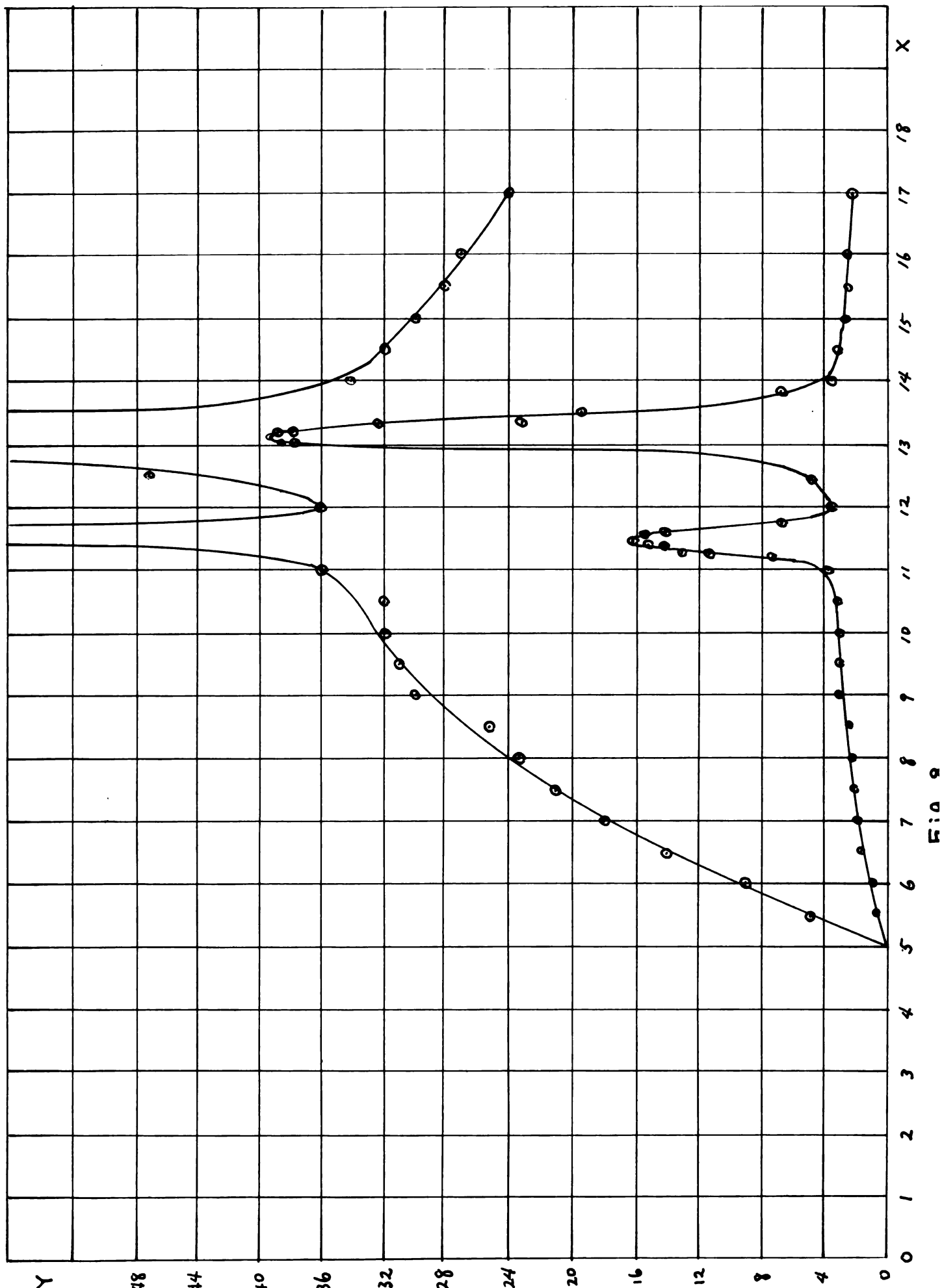


FIG 9

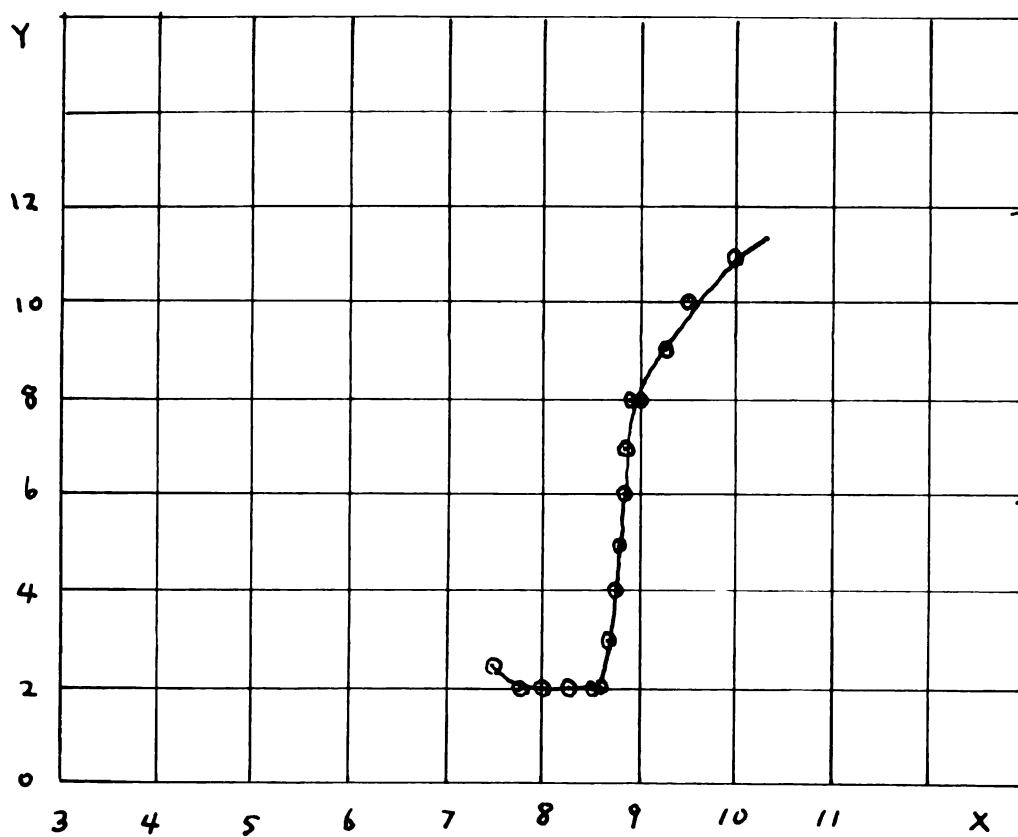


Fig. 9

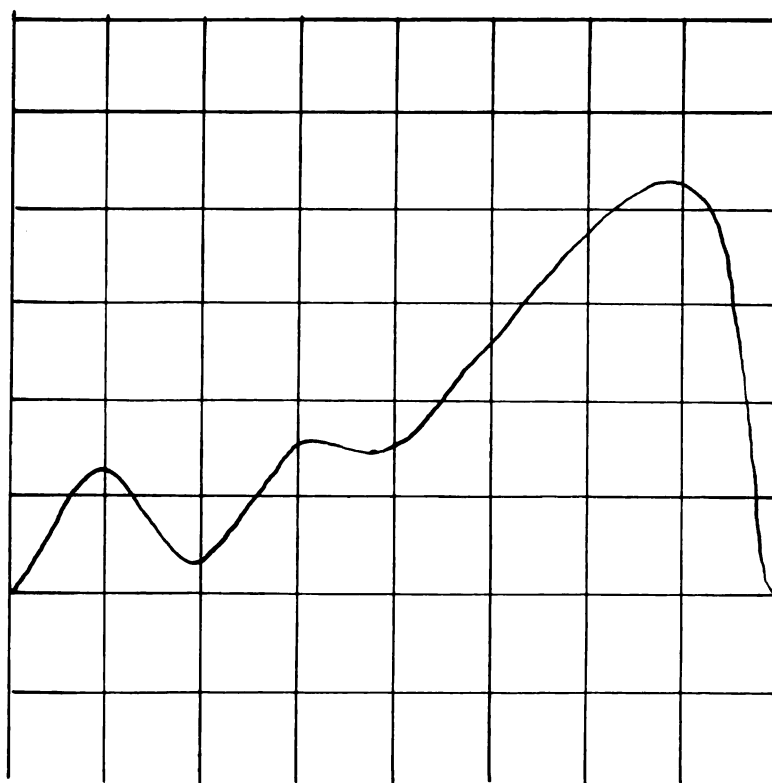


Fig. 10

IV CONCLUSION

With this unit, some analytical study of continuous x-rays, measurement of absorption edges, and taking **Laue** and powder pictures can be done quite satisfactorily. One weak point of this apparatus is that the insulation of the rectifiers begins to break down in the neighborhood of 50 kilovolts, particularly along the outer surface of the glass envelope from anode **base** to filament leads, and especially when it is run for long periods.

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