DESIGN AND CONSTRUCTION OF A KILO-VOLTMETER FOR USE WITH X-RAY MACHINES

Thesis for the Degree of M. S.

William Richard Struwin

1935

Volt-meter

Title Kilo-voltmeter

Physics

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I wish to express my sincere appreciation and gratitude to the Staff of the Physics Department, and especially to Professor O. L. Snow under whose direct supervision this thesis was made possible.

W. R. Struwin

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Part 11

Introduction

The development of X-ray generating equipment has been so rapid that control and measurement instruments have lagged behind. Perhaps the most important measurement to be made is that of the kilovoltage applied to the X-ray tube. Upon this depends the wave-length of the X-ray beam as well as the energy content and thus the penetration of the same. A continous indicating kilo-voltmeter might well be considered the most useful instrument in the X-ray laboratory.

In view of the fact that there is no such instrument in existance for general use it was the purpose of this work to study the various more or less makeshift methods now used and to design and construct an instrument which would be more satisfactory.

Part 1 is a description of the X-ray power plant that was assembled for general use and also for testing experimental kilovoltmeters, together with instructions for operating the same.

Part 11 is a report on the method developed in this laboratory as well as a suggested outline for future study of kilovoltmeters.

PART 1

X-RAY GENERATING EQUIPMENT

1. Nature of X-rays

X-rays were discovered by Roentgen in 1895 while he was performing some cathode ray experiments. Both the terms Roentgen rays and X-rays are applied to the same phenonema.

Early investigations showed the similiarity between these rays and ordinary light. They pass through space in straight lines, affect a photographic plate, are unaffected by electric and magnetic fields, and show polarization and many other well known effects common to light, but in some respects they differ. They can not be reflected, refracted, or diffracted as can light by ordinary means. In recent years, however, these effects have been produced by elaborate methods. X-rays may be reflected and diffracted from crystal planes, and by this means X-ray wave length is measured, and also, using a known wave length the structure of unknown crystals may be determined. X-rays are, like light, electromagnetic waves varying in length from 0.06 to 1019 Ångstrom Units, thus fringing the gamma rays on one side and ultra violet light on the other.

All electromagnetic waves are produced by some form of an electrical disturbance. X-rays are produced when a high speed electron or cathode beam strikes a metal target. X-rays travel in straight lines with the velocity of light, losing intensity according to the inverse square law. They are produced when cathode rays strike matter of any kind and are thus suddenly stopped. They may also be emmitted when X-rays fall upon a given substance, being given off as secondary radiation of longer wave length. Thus in order to produce a primary beam of X-ray it is necessary to have a source of cathode rays striking a dense target at high velocity. This is the purpose of all X-ray apparatus.

The energy content of the X-rays depends upon their intensity and also the wave length, the shorter the wave length the greater the inherant energy.

11. Uses of X-rays

In medicine X-rays play an ever increasingly important part, both in radiographic and theraputic

uses. They assume an important place in industrial laboratories for the examination of articles such as castings, welds, etc., without destroying the sample. Engineers now use X-rays to determine the effects of stress and strains in structural materials, as well as effects of various heat treatments. The technique of welding and pouring of castings has likewise been improved.

X-rays have played an important part in the development of rayon.

They are very active biologically and are now being used to disturb the genes in plant and animal life. Some evolutionary processes are said to be accelerated as much as 3000% by X-ray treatment.

Many substances behave very differently in chemical reactions after they have been treated with X-rays, and the study of this phenonema offers a fertile field for research.

In the physics laboratory they have a wide application in the study of crystal structure and enable a more intensive study of the ultimate structure of matter.

111. X-ray Equipment

The facilities of the X-ray laboratory of the Physics department of Michigan State College have been increased during the past two years by the addition of a larger capacity X-ray equipment which was formerly used at the Michigan State Tuberculosis Sanitorium at Howell, Michigan. This equipment is old style and rather obsolete in medical practice, but is quite satisfactory in laboratory and experimental work. It is designed for maximum continuous operation at 100 milliamperes at 100 Kilovolts, but these limits may be exceeded for short periods without harm.

A part of the laboratory work incidental to this thesis was the repair, assembly, and installation of the several parts of this equipment, involving among other things permanent wiring for both the input power and high voltage output; a magnetically controlled time switch, an auto-transformer control, and a new filament transformer with ammeter for the same.

A large fluoroscope on a separate stand, a tube stand, a medical table, a "bucky" filter, intensifying screens, and one new type Westinghouse tube were other parts of the equipment.

There is now equipment for practically any kind of medical work as well as a substantial power plant for work in castings, crystal analysis and other work in modern physics.

IV. The X-ray Power Plant

Since all X-ray tubes require a high voltage the essential part of every machine is the means of production of the high voltage. In all modern machines this is a step-up transformer. In order to control the output, rheostats or auto-transformers or both are included in the primary circuit, as well as time switches and safety devices. The output of the high voltage transformer is then usually rectified either by a mechanical or a vacuum tube rectifier. In small outfits the X-ray tube itself may be used for the rectifier, provided it is of the Coolidge type with means for keeping the target cool. Where Coolidge type tubes are used provision must be made for the filament supply with additional resistances in this circuit. The meters that are usually used consists of a milliammeter and a filament ammeter.

Some means of estimating the kilovoltage, such as a spark gap, is usually included.

Additional refinements may be added to the X-ray equipment depending upon the amount of money available, and each have special purposes for which they are useful. It is good economy to invest as much in safety equipment as possible.

V. The Power Supply

The power supply for the X-ray machine here being described is taken directly from one phase of the 2300 volt primary line through a 15 K.V.A. step down transformer and led through special #2 wires to an enclosed switch in the X-ray laboratory. It is fused at 100 amperes. The line supplies 220 volt alternating current at 60 cycles and is used solely for the X-ray equipment. Connected directly to the switch is an automatic instant acting circuit breaker. This consists of a coil in one of the leads wound upon an iron core and which attracts an iron armature with a force proportional to the current passing through the coil. If the current should even momentarily become too great, this armature flies upward and

strikes the small triggers which engage the switch arms, and cause them to release. Then they fly open by both gravity and spring action. The construction of these switch arms is interesting. The main current is carried by large copper contacts. When the switch is released these copper contacts separate, but the current still passes for an infinitesimal time through large carbon block contacts. When these release all of the arc incident to the breaking of the circuit occurs at the carbon contacts, and does no damage to the main copper current carrying contacts. These carbons may be replaced easily if necessary. In case of an overload this circuit breaker disconnects both sides of the line simultaneously. The circuit breaker is adjustable for different current ratings by varying the set screw below the armature; the farther this armature is away from the magnet core the more current it will take to attract it. A scale shows the approximate current ratings, and the circuit breaker should be set at approximately 75 amperes. The power is carried to the auto-transformer through #4 wires enclosed in flexible metalic tubing.

No other power devices should be used from the power supply line when the X-ray machine is being used, although it is a suitable source of power for operating motors etc., when the X-ray machine is not in use.

The power for other pieces of X-ray equipment is taken from the load side of the main supply switch.

VI. The Auto-transformer

An auto-transformer consists of a large closed laminated iron core with a single winding of wire sufficiently heavy to carry the highest current used. It is provided with a large number of taps on different turns and thus a large number of different voltages may be tapped off from the transformer. The operation of an auto-transformer is similiar to the operation of any other transformer, in that the output voltage across any number turns depends upon the ratio of that number ot turns to the total number of turns connected to the power supply voltage. The auto-transformer is designed for a 220 volt drop across the entire coil and hence 110 volts across one half of the coil.

There is mounted on the auto-transformer control panel a single pole double throw switch, two movable arms making contact on rows of contact points, and a meter calibrated in kilovolts. Inside of the case as a binding-post strip wired to the various taps, and from which connection is made through heavy multiple conductor cable to the X-ray machine. Since the supply is 220 volts, it is connected directly across the entire transformer coil.

Leads are run from the various taps on the auto-transformer to the binding-post strip which in turn supplies several constant voltages as long as the line is connected and is independent of the main transformer control settings of the auto-transformer. The taps are marked for simplicity and convenience as follows: -110 volts; 0 line; -T; 0; +T; +70 volts; + 110 volts. This marking was chosen for convenience, and the + and - signs have no significance since alternating current is used, and hence there is no such thing as positive and negative in the literal sense of the word. These markings merely mean that, considering the mid-point as at earth potential, there is 110 volts potential between it and either side of the coil, and across the whole coil there is a total of 220 volts. This method of marking is purely arbitrary, but may be easily followed to obtain the desired voltage combinations. This strip is also lettered with corresponding letters on the machine switchboard binding posts.

These several taps on the binding-post strip are connected by leads to the different circuits as follows: The main power supply leads are connected between the -110 and the + 110 volt terminals. The grounded center tap of the power supply is connected through the 0 line binding post to one side of the single pole double throw switch on the auto-transformer switchboard panel and to the center tap of the auto-transformer. The other side of this switch is at present not connected to anything. When this circuit is closed by means of this switch, better regulation of the output is obtained when the load of the auto-transformer is considerably unbalanced with respect to the two sides of the coil. The motor circuit is connected between - 110 and 0, and accordingly receives 110 volts for its operation. The 220 volts required by the magnetic time switch is taken from the two taps which are labeled + 110 and - 110.

The motor circuit is protected by a 30 ampere fuse mounted on the binding post strip together with a 2 ampere fuse protecting the filament transformer.

Two binding posts are provided marked + T and - T which are connected to the movable arms on the control panel. These arms pass over contacts connected to various coil taps, and hence may be set at any desired value. The one arm gives a coarse adjustment while the other arm provides a fine adjustment. One step of the coarse adjustment just equals the entire range of the fine adjustment arm. Every other step over which the control arm passes is a blank having no connection, and thus the control arm must be moved two steps to make one change. The reason is that as the control arm is moved over the contacts, it would short circuit adjacent contacts as it passed over them. This would be equivalent to short circuiting turns, which would cause a large current to flow, and might over heat the transformer winding.

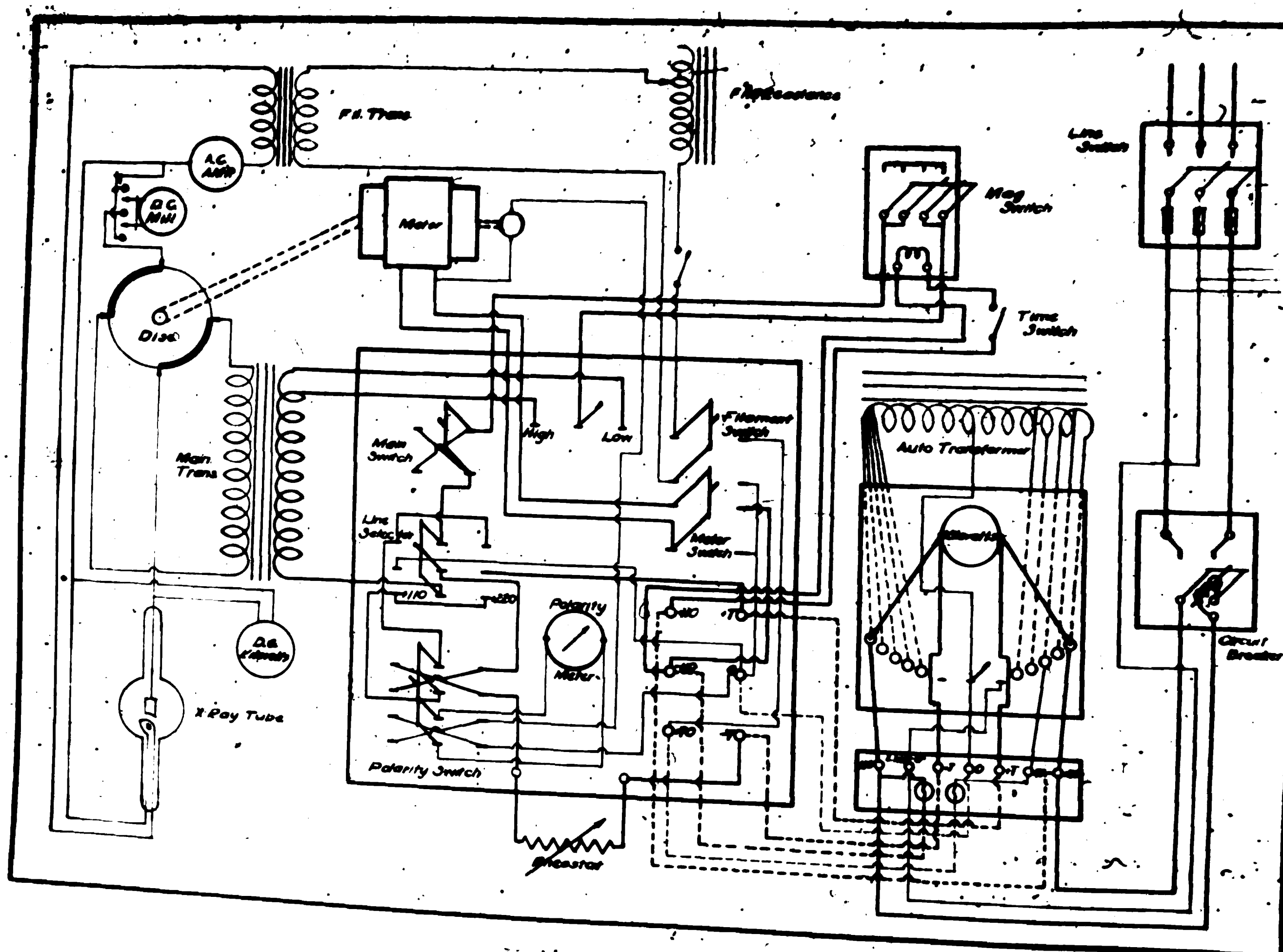
The main high voltage X-ray transformer is connected by doubled extra heavy wires in the cable to these variable arms, and a meter graduated in kilovolts is connected between them. This meter is really a voltmeter requiring 220 volts for full scale deflection and having a scale divided into 100 divisions labeled kilovolts. This calibration is based upon the step-up ratio of the main transformer, taking into account the voltage drop due to the resistance of its windings and the voltage loss in the rectifier. Hence it applies for only one value of tube current, and is far from accurate at any other load. The tube current to use with this calibration is 20 milliamperes. To use a smaller number of milliamperes the effective kilovoltage would be greater than that shown by the meter, being nearly doubled if the tube current is cut in half. The opposite effect is noted when the tube current is increased, that is, the effective kilovoltage is greatly lowered. These effects are entirely due to resistance losses in the high voltage system and cannot be eliminated. The only solution is to use the standard technique at all times, and accept the kilovoltage indications as given by the meter.

All of the electrical connections referred to above as well as those that follow may be traced on the main wiring diagram on page 14.

VII. Synchronous Motor and Rectifier

The rectifier used to supply the tube with unidirectional high voltage current is of the mechanical type and is operated by a synchronous motor. A synchronous motor is a motor that always stays in step with the alternating current input, and is so designed that the rotor shaft is always at a certain position when the wave is in a definite phase. The rotor of the motor is always at the same electrical position as the rotor of the alternator supplying the current.

The motor is constructed the same as any stator wound split phase induction motor, except the rotor, instead of having alternate iron and copper bars, has four extra wide copper bars



Main Wiring Diagram

placed at 90° intervals around the rotor. These tend to prevent the rotor from slipping phas and "lagging" the current. The load is very small and the motor is one horsepower, so that there is little tendency for the rotor to lag, and these portions of non-magnetic material prevent any change of phase position once the motor has started. The starting winding consists of a few turns of wire in such a position that the torque is greater in the direction of rotation. When the motor has gained speed this starting winding is disconnected by means of a centrifugal switch, which breaks contact with two stationary slip rings connected in series with this winding. The switch has two electrically connected arms which rotate on these slip rings and are held against them with springs. When the speed is sufficient these contact arms are thrown out by centrifugal force against the force of the spring, and break contact with the slip rings. The whole switch is electrically insulated from the frame. The motor is connected to the line by means of a double pole single throw switch located on the switchboard of the X-ray machine. It operates from the 110 volt circuit and draws approximately 8 amperes while running. It does not heat greatly under continuous operation, and it is a better policy to allow the motor to run continuously while taking a series of exposures than to turn it off and on repeatedly.

The rectifying disc consists of a circular sheet of mica about 24 inches in diameter rigidly attached to the synchronous motor shaft and having metal strips at each quadrant, adjacent strips being electrically connected, giving, in effect, a disc with two conducting and two non-conducting quadrants. Four brushes placed 90° apart make contact with this disc. Two of them, 180° apart, are connected to the transformer terminals, while the other two supply rectified current to the tube. These brushes are carefully insulated by large stand-off insulators and the connecting leads are enclosed in mica tubes.

Referring to page 17, it is seen that in position one, brushes A and D are connected and B and C are also connected. If the alternating current is at the proper phase angle to make brush

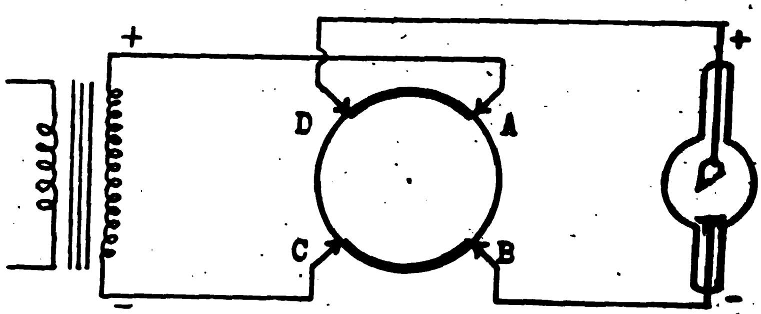


Fig. 1.

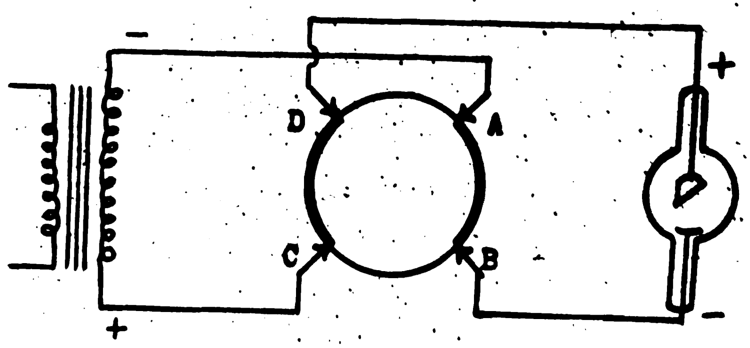


Fig. 2.

Mechanical Disc Rectifier.

A positive, then brush D would also be positive, and brush B would be connected to brush C, and that line would be negative. At a phase angle 180° beyond this point, brush A would be negative and C positive. But the action of the synchronous motor during this time would have caused the disc to be so rotated that A would be connected to B (position 2) and C would be connected to D. Thus the line D would still be positive and B would remain negative. Since both motor and transformer are connected to the same power supply the synchronous motor will follow the reversals of the current in the same manner as the transformer, and rectification will always be in the same direction.

The use of the mechanical rectifier allows only the peak of the wave to pass and the low voltage portion of the wave is shut off. This is an advantage, since this portion is not useful in the production of penetrating X-rays and merely serves to heat the target, which becomes overheated all too quickly with its own peak current. It is interesting to note that as little as 2% of the electrical energy is converted into X-rays, the rest being dissipated as heat. More modern systems of rectification use one or more high voltage kenotron tubes in different circuits as shown on page 20. They are similiar to X-ray tubes and have a filament and anode. The filaments are heated by separate filament transformers, the primaries of which are connected to the 110 volt supply line. These tubes pass an electron current from the filament to the anode only, and none in the opposite direction. Their action in the different circuits may readily be seen in the diagram.

The wave form with disc rectification is more or less complex and does not follow the theoretical. This is due to the fact that the spark starts to jump before the disc reaches the brush and holds after the disc has passed the brush. This produces a complex form that is hard to measure and interpret.

The synchronous motor will start without regard to polarity, and thus either side of the high voltage might be rendered positive. Since the tubes are usually left connected to the line with a certain polarity and since there is no convenient method of determining the polarity of the high voltage, an auxilliary means of determining and controlling the polarity must be provided. For this purpose a polarity indicator is placed on the machine switchboard together with a polarity reversing switch. The polarity indicator is really a direct current voltmeter with the zero in the center of the dial. As shown by the main wiring diagram, (page 14), the meter is operated from the A.C. motor supply through a small commutator on the end of the synchronous motor shaft. This commutator has four quadrants, two opposite ones being connected together and the other two insulated from one another. Two brushes are in contact with the commutator 180° apart. If, when the supply line (-110) is positive the two brushes are connected by being in contact with the two commutator bars which are connected together the meter will indicate in the positive direction. When the line (-110) is negative the motor has turned far enough so that the brushes are disconnected by being in contact with the other two commutator bars. Due to the inertia and damping of the meter needle, it will give a steady positive indication, the meter return being to the other motor line (0). Should the motor start up on the other half cycle the meter would give a negative indication.

From the main wiring diagram (page 14) it may be seen that the transformer supply leads and also the meter connection wires pass through a polarity switch of a four pole double throw type located on the machine switchboard. Two poles are used for each circuit. By reversing this switch the meter may be made to read positive if it should at any time read negative at first, the transformer connections being thus automatically changed also to make the correct polarity of the rectified current. Whenever the motor is started the polarity indicator should be made to indicate positive after the motor has reached synchronous speed. The polarity will not change unless the current supply is interrupted. It is very important to always have the correct polarity, since a high reverse voltage is highly injurious to the tubes connected, especially those of the gas variety.

V111. Care of Motor And Machine

The motor should be oiled in both bearings once a month with a good grade of machine oil and inspected to see that the oil rings are rotating properly. All connections should be inspected for tightness and the set screws that hold the mica disc in place on the shaft should be tight. The brush holder for the polarity indicator commutator may be rotated if necessary by loosening the set screw and turning the brush holder until the meter gives a maximum deflection. The high voltage contacts should be occasionally cleaned and adjusted so as to just miss the disc contacts as they pass. The disc will not rotate on the motor shaft because it is held in place with a machine key. The disc has been adjusted for maximum efficiency under prevailing conditions.

lX. Filament Supply

The filament supply comes from the 70 volt tap on the autotransformer and is controlled by a double pole single throw switch on the machine switchboard. From the switch the power passes through a variable reactance coil and from there to the primary winding of the filament transformer. Both the reactance and the filament transformer are set on top of the X-ray machine and elevated by insulators to prevent a breakdown between the high voltage wires in the X-ray machine and the filament circuit. The reactance controls the primary current, and hence indirectly the secondary current. The primary is rated at 80 volts 60 cycle alternating current. About one ampere is required through this primary. This transformer is of the ordinary step down type, except an extremely high voltage insulation is provided between the primary and secondary windings. The secondary is rated at from 5 to 20 volts and up to about 5 amperes. The transformer has an iron case with a fiber top and a high pillar of bakelite from which the filament leads emerge. It is of the oil filled type and will stand 100 kilovolts between windings. An alternating current ammeter is connected to the output and has a 0-10 ampere range. The filament current should be between 4 and 5 amperes for normal operation. When the filament is cold its resistance is much lower than when it is hot, and since it has quite a large thermal capacity it draws a very large current while it is warming up. This is hard on the filament, transformer, and ammeter. The remedy is to always turn the switch on when all the reactance is included in the primary circuit, and gradually increase the current as the filament warms up.

One of the filament lines is connected directly to the negative high voltage line which is thus made to serve two purposes and the other filament line is a # 14 rubber covered wire passing inside the high voltage conductor, thence to the tube.

X. High Voltage Lines

The high voltage lines are made of copper tubing to give the necessary rigidity and to prevent corona losses. The larger the conductor the less the corona loss. A 14 inch separation is provided between the ceiling and walls, and the conductors are $7\frac{1}{2}$ feet above the floor. The positive lead terminated in a hook fastened to a flexible lead which is kept under constant tension by a spring operated take up reel. This engages a loop which serves as the anode terminal of all Coolidge tubes. The two filament wires connected to the negative line terminates in a medium Edison style screw receptacle which fits the cathode end of the Coolidge tubes. The leads are kept taut by means of spring driven reels. These leads are prevented from making accidental contact by short lengths of rubber tubing.

XI. Switch Board

Most of the controls on the X-ray switchboard have been discussed, but are here reviewed from the standpoint of machine operation. In the upper right hand corner of the control board is a double pole single throw switch in the filament primary circuit. A similiar switch just below controls the motor. The polarity switch is in the lower left hand corner. Above this is a triple pole double throw switch formerly used to connect the transformer to either 110 or 220 volt line. In its present use it is left on the 220 volt side and in that position it is connected directly to the variable taps of the auto-transformer. Above this is a double pole single throw switch used formerly as the main transformer control switch, but has since been replaced by the magnetically controlled time switch. This double pole switch has been left in the line however, and is used to disconnect the main transformer between exposures so that the inadvertant closing of the time switch will not turn on the high voltage. A single pole double throw switch connects one of the line wires to either of two taps on the primary of the transformer, and thus gives two slightly different voltage ranges. A variable rheostat, in the primary circuit, is located just below the switchboard and is used exclusively for voltage control when the old-style gas type tubes are used. It is left with the resistance all out when using Coolidge type tubes, control being effected by the auto-transformer and filament reactance. The reason for including resistance in the primary circuit when a gas tube is being used is because the pressure is apt to change suddenly and if it does a very large current might flow causing considerable damage. A resistance protects the primary circuit from excessive power and tends to keep the action of the gas tube more constant.

XII. Time Switch

The time switch is of the Cutler Hammer magnetic control variety having a large current rating and is designed to break the circuit in four places, thus preventing any tendency to arc across contacts. It is connected in series with the primary of the transformer. The 220 volt current supply for this switch has been discussed on page 11.

This small current passes through the small portable hand switch with clockwork control. For continuous operation the button on the top of the switch is held down during the exposure. This merely completes the circuit by means of a push-button arrangement. If it is desired to set the switch for a definite time interval, the clockwork mechanism is wound up by means of the small knob on the front until the pointer indicates the desired time. The exposure is made by pressing the knob on the top until the clock runs down, the current automatically shutting off at the end of the exposure. The time indicator may be set 1/8 second minimum. The maximum time setting is 12 seconds, but the clock may be quickly rewound and the exposure continued if necessary. If this switch is wound beyond the desired time it may be run down by pressing the top button, providing the main line switch on the main switchboard has first been opened. This portable hand switch is in a bakelite case and great care should be taken not to drop it since the case would break easily. The switch is quite expensive and must be carefully handled.

For long exposures in some physical work a cord with a simple cord switch is provided and may be plugged in, in place of the time switch and the primary of the transformer thus controlled.

X111. Main Transformer

The high voltage transformer is an extra large style transformer with about 15 K.V.A. capacity. It has a heavy primary winding on a massive iron core and a secondary winding capable of delivering 100 milliamperes continuously. The secondary voltage is delivered to two mica pillar insulators. The mid-point of the secondary is grounded. The case is of welded sheet steel and the top is of fiber, well bolted to the transformer case. The transformer case is oil filled and should be kept to within one-half inch of the top with high grade transformer oil. The plug over the filler opening should be kept closed to exclude moisture.

After the high potential current has been rectified it passes through a dual range milli-ammeter. The lower range reads to 30 milliamperes and the upper reads to 200 milliamperes. This meter being part of the high voltage system is mounted in a well insulated position on top of the cabinet and in easy view of the operator while in position to adjust the filament current.

XIV. Tube Stands

Tube stands are of very heavy and sturdy construction and are so arranged that the tube may be adjusted to almost any height. The tube when in position is counterbalanced and may be handled very easily. Tube stands are equipped with a lead glass bowl, and thus provide protection from X-rays except in the direction where X-rays are desired. A modified tube stand with the tube completely enclosed in a lead covered box is used in connection with a fluoroscope for visual examination of a patient.

Tubes may also be mounted underneath adjustable tables so that the patient may be observed by means of a fluoroscope while in a prone position.

Special mountings which give utmost protection from X-rays must be used for physical research work.

XV. Tubes

The gas filled tubes are now obsolete and only the high vacuum filament tubes will be discussed. The filament or Coolidge type tube in the universal form consists of a highly evacuated glass bulb about

10 inches in diameter, having two side arms about one inch in diameter projecting from opposite ends of a diameter to a distance that will make the entire tube about 30 inches long. The two electrodes are sealed into these side arms and the terminals are located at the ends of these arms. The electrodes which are supported in the tube about 2 inches apart consists of a cathode and anode or target. They will be discussed separately.

The cathode or electron source consists of a small coiled filament from which a plentiful supply of electrons are given off. The outer casing of the cathode is of such shape as to direct the electron stream or cathode ray by means of its electrostatic field to a sharp focus point where the electrons strike the anode. The number of electrons which the filament may give off per second depends solely upon its temperature for a given filament material, and may be determined theoretically from Richardson's equation:

$$i_s = a' T^{\frac{1}{2}} e^{-\phi/kT}$$ in which

i_s = current, T = absolute temperature, k = Boltzman's constant, a' & ϕ are constants depending upon the filament. A graph of the tube currents for various filament currents is given on page 33.

Since the tube voltage is very high all of these electrons are drawn to the target and the tube current is limited by this supply. Thus the filament reactance is used as the sole control of the milliamperes that are being used. The amount of X-rays given off is the product of the milliamperes and the time that they act. Thus 20 milliamperes acting for two seconds will have the same effect as 4 milliamperes acting for ten seconds. The penetrating power of X-rays depends upon the kilovoltage used and is controlled by the auto-transformer.

The anodes or targets usually used are of a heavy metal such as tungsten or Molybdenum and are mounted on copper or Molybdenum support. Various means are provided to dissipate the heat energy produced. In the universal type tube the entire anode is of tungsten and is allowed to become white hot, in which state it radiates energy as fast as it is supplied. Other tubes have fins so that the heat may be carried off by convection air currents. Others have large masses of copper in which the heat is intermittantly

TABLE IX

Filament Current	*Tube Current*
3.09 amp.	0.6 ma.
3.31	2.5
3.40	4.4
3.50	8.2
3.57	12.5
3.67	20.7
3.65	22.2
3.71	27.0
4.13	35.4

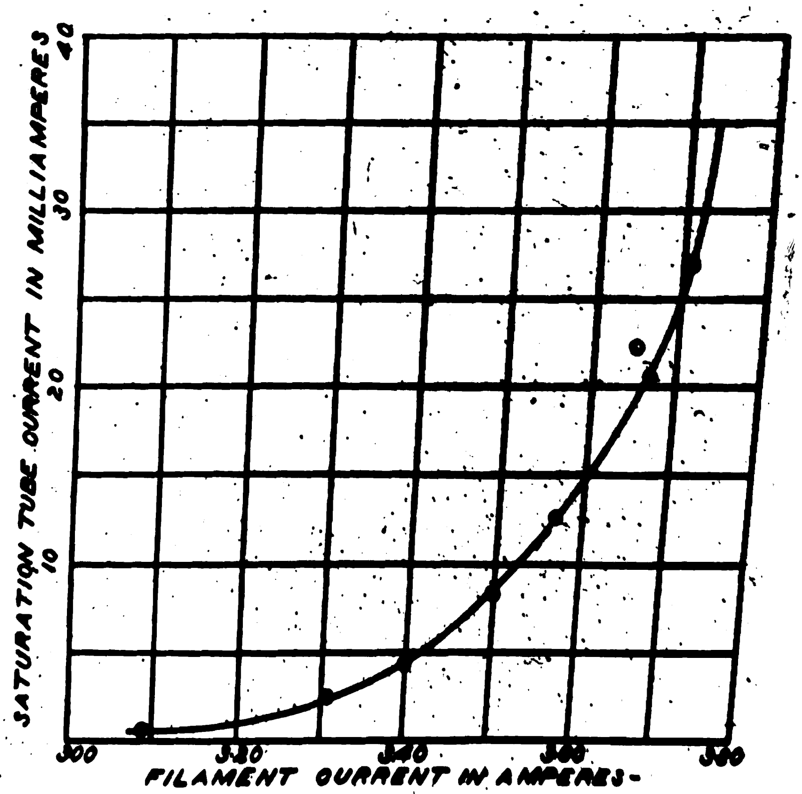


FIG. 68.—Graph showing variation of (saturated) tube current with filament current.

stored. Such tubes are not suitable for continuous duty. Other tubes are water or oil cooled for continuous duty. A Westinghouse Radiographic tube is now included in the laboratory equipment. (Fig. on page 35) Here electrons from the filament pass upward and are focused on the target. The X-rays given off are shielded in all directions except directly down through the center of the coiled filament by means of a heavy iron cylinder. The bottom window is very thin pyrex glass and offers very little obstruction for the X-rays. The tube may be used with high energies for short times, cooling being effected by the massive copper storage stem and the fin radiator on the top. The filament connections are made to the two metal knobs at the base of the tube and the anode connection to the radiator at the top. A special holder supplied with this tube enables it to be used on the standard tube stand and connection to the line is the same as for the standard Coolidge tube. Thus this tube may be used interchangeably with other types of tube without making any changes either mechanically or electrically in the apparatus. The following table shows the maximum time-current

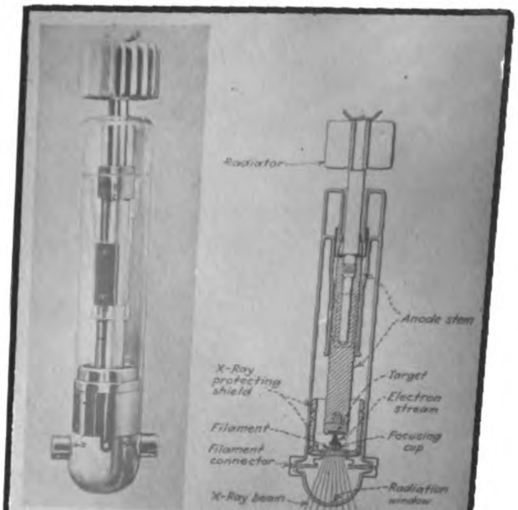
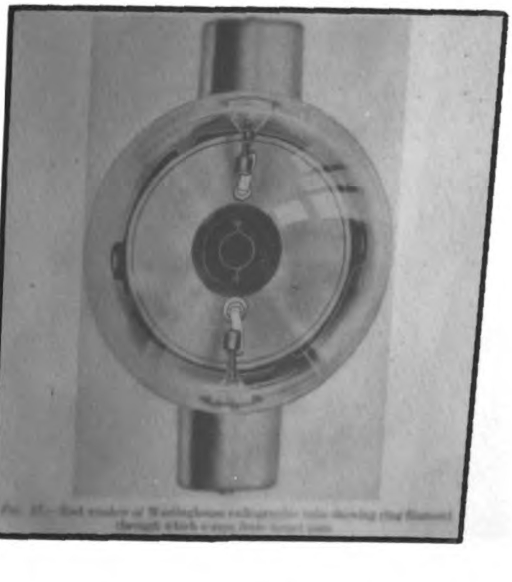


FIG. 15. FIG. 16.

FIG. 15.—Photograph of new Westinghouse radiographic tube.
FIG. 16.—Diagrammatic construction of tube pictured in Fig. 15.



Westinghouse X-ray Tube

WESTINGHOUSE--RADIOGRAPHIC TUBE

Full Wave Rectifier--Maximum filament current about 5 amps.

Tube Current	Time 90 K.V.	Time 85 K.V.	Time 80 K.V.	Time 75 K.V.	Time 70 K.V.
10 Ma.	150.0 Sec.	150.0 Sec	150.0 Sec	150.0 Sec	150.0 Sec.
30 "	24.0 "	27.0 "	30.0 "	33.0 "	36.0 "
60 "	4.0 "	5.0 "	6.5 "	7.25 "	9.5 "
75 "	1.5 "	2.0 "	2.75 "	3.5 "	4.5 "
100 "	0.2 "	0.4 "	0.6 "	0.9 "	1.25 "

ratings of this tube when used with full wave rectified current.

XVI. X-ray Technique

The operation of the X-ray machine is quite simple, once it is properly installed and adjusted. The first operation is to start the motor and adjust the polarity. The filament is then lighted and the ammeter set at the desired value depending upon the current to be used. The tube is adjusted at the desired distance from the subject, the film or plate within its holder being at this point in the proceedure safely within a lead lined box near at hand. The high voltage leads should be at least 14 inches from each other or from the tube stand or patient. The auto-transformer is set for the desired kilovoltage and also the rheostat if necessary. The high voltage is turned on and the final adjustment of the milliamperes is made with the filament rheostat. The film holder is then removed from the lead storage box and placed usually under the subject with the tube on the opposite side of and usually above the subject about 30 inches. The correct exposure is made using the time switch. The film should be developed immediately.

The operator and observers in the X-ray room cannot be too cautious in their work around the high voltage lines, and incidently the low voltage ones. A person might easily receive a very serious if not fatal shock from this high voltage system which is capable of jumping a distance of nearly a foot.

There is just as much danger from every line to ground as there is between lines. In addition the X-rays themselves are exceedingly dangerous and due to their cumulative effect will cause considerable damage to a person working with them day after day. Both the operator and the patient should be protected from them by having the tube enclosed in a lead box or else in a lead glass bowl. Where large pictures are not necessary the protective cones that fit below the tube should be used. To guard against electrical shocks the floor should be made as insulating as possible by covering with wood, linoleum, rubber or glass stools. The operator should keep the time switch in his hand all the time and instantly open it if there appears to be any trouble.

Films are expensive and a human life far more precious. It is the operators responsibility to see that the equipment is operating properly before placing the films or patient under the machine. It should always be tested under the same conditions as the exposure is to be made.

The operator will save many spoiled films by checking the operation with the fluoroscope first.

The proper kilovoltage setting to be used and the correct number of milliampere seconds for different parts of the body may be determined from the Westinghouse chart herein reproduced (on page 40). It gives the distance from the target of the tube to the film, and the milliampere seconds for the various parts when using the film in plain holders or intensifying screens, and also when the bucky diaphram is used. Reference is then made to the proper scale below. This scale gives the kilovoltage setting for the various part thickness in centimeters. With a little practice very good results may be obtained through the use of the chart.

Measurement of Part X-Ray Technique Chart

EDUCATIONAL DEPARTMENT

Westinghouse X-Ray Company, Inc.

LONG ISLAND CITY, N. Y.

Measurement of Part X-Ray Technique Chart

SCREENS "French"
FILMS Eastman "Duplitized"

LINE
DATE 5/15/'33

EXTREMITIES – NON-SCREEN

PART	Adults Distance	Adults M.A. Seconds	Adults Scale	Adults Soft Tissue M.A. Seconds	Adults Soft Tissue Scale	Aged M.A. Seconds	Aged Scale	Aged Soft Tissue M.A. Seconds	Aged Soft Tissue Scale	Children M.A. Seconds	Children Scale	Infants M.A. Seconds	Infants Scale
FINGERS, TOES	30	75	4	35	4	55	4	35	4	55	4	20	4
HAND, FOOT	30	75	4	35	4	55	4	35	4	55	4	20	4
WRIST, ANKLE	30	75	4	35	4	55	4	35	4	55	4	20	4
ELBOW, KNEE	30	75	4	35	4	55	4	35	4	55	4	20	4
FEMUR	30	75	4	35	4	55	4	35	4	55	4	20	4
SHOULDER	30	75	4	35	4	55	4	35	4	55	4	20	4

EXTREMITIES – WITH SCREENS

PART	Adults Distance	Adults M.A. Seconds	Adults Scale	Adults Soft Tissue M.A. Seconds	Adults Soft Tissue Scale	Aged M.A. Seconds	Aged Scale	Aged Soft Tissue M.A. Seconds	Aged Soft Tissue Scale	Children M.A. Seconds	Children Scale	Infants M.A. Seconds	Infants Scale
FINGERS, TOES	36	50	1	100	5	35	1	75	5	35	1	15	1
HAND, FOOT	36	50	1	100	5	35	1	75	5	35	1	15	1
WRIST, ANKLE	36	50	1	100	5	35	1	75	5	35	1	15	1
ELBOW, KNEE	36	50	1	100	5	35	1	75	5	35	1	15	1
FEMUR	36	50	1	100	5	35	1	75	5	35	1	15	1
SHOULDER	36	50	1	100	5	35	1	75	5	35	1	15	1
	36	50	1	100	5	35	1	75	5	35	1	15	1

MISCELLANEOUS – WITH SCREENS

PART	Adults Distance	Adults M.A. Seconds	Adults Scale	Aged M.A. Seconds	Aged Scale	Children M.A. Seconds	Children Scale	Infants Distance	Infants M.A. Seconds	Infants Scale
HEAD, A. P.	30	60	1	50	1	50	1	30	25	1
FRONTAL SINUS	30	50	1	40	1	40	1	30	20	1
ETHMOIDS	30	75	1	60	1	60	1	30	30	1
SPHENOIDS	30	75	1	60	1	60	1	30	30	1
MASTOIDS, LAT.	30	75	1	60	1	60	1	30	30	1
LATERAL SKULL	30	50	1	40	1	40	1	30	20	1
DORSAL SPINE, A. P.						35	1	30	20	1
DORSAL SPINE, LAT.						35	2	30	20	2
LUMBAR SPINE, A. P.						50	1	30	25	1
LUMBAR SPINE, LAT.						100	2	30	50	2
PELVIS, A. P.						40	1	30	20	1
KIDNEY, A. P.						40	1	30	20	1
RIBS BELOW DIAPH.						40	1	30	20	1
GALL BLADDER	30	50	1	50	1	50	1	30	50	1
STOMACH & COLON	30	50	1	50	1	50	1	30	50	1
CERVICAL SPINE, A. P.	48	50	4	50	4	50	4	36	25	4
CERVICAL SPINE, LAT.	48	50	4	50	4	50	4	36	25	4
CHEST & HEART, A. P.	72	10	3	10	3	10	3	36	10	1
CHEST & HEART SEMI OBLIQUE	72	10	3	10	3	10	3	36	10	1
CHEST & HEART, LAT.	72	10	2	10	2	10	2	36	10	1

MISCELLANEOUS – WITH BUCKY

PART	Adults Distance	Adults M.A. Seconds	Adults Scale	Aged M.A. Seconds	Aged Scale	Children M.A. Seconds	Children Scale
HEAD, A. P.	30	175	1	150	1	150	1
FRONTAL SINUS	30	150	1	125	1	125	1
ETHMOIDS	30	225	1	175	1	175	1
SPHENOIDS	30	225	1	175	1	175	1
MASTOIDS, LAT.	30	225	1	175	1	175	1
LATERAL SKULL	30	150	1	125	1	125	1
DORSAL SPINE, A. P.	30	150	1	125	1	125	1
DORSAL SPINE, LAT.	30	150	2	125	2	125	2
LUMBAR SPINE, A. P.	30	200	1	150	1	150	1
LUMBAR SPINE, LAT.	30	350	2	275	2	275	2
PELVIS, A. P.	30	175	1	150	1	150	1
KIDNEY, A. P.	30	175	1	150	1	150	1
RIBS BELOW DIAPH.	30	175	1	150	1	150	1
GALL BLADDER	30	50	3	50	3	50	3
STOMACH & COLON	30	50	3	50	3	50	3
CERVICAL SPINE, A. P.	30	100	4	75	4	75	4
ATLAS & AXIS, A. P.	30	100	4	75	4	75	4
SHOULDER	30	100	1	75	1	75	1
FOETAL, P. A.	30	175	1				
FOETAL, LAT.	30	175	1				

THICKNESS OF PART IN CENTIMETERS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SCALE #1		40	41	42	43	44	45	46	47	48	49	50	52	54	56	58	60	62	64	67	70	73	76	80	83	87									
SCALE #2																					54	56	59	62	66	70	74	78	82	86	90	Kilo volts necessary for penetration			
SCALE #3												63	65	67	69	71	73	75	77	79	80	85	88												
SCALE #4	47	49	51	53	55	57	59	61	63	65	67																								
SCALE #5				33	34	35	36	37	38	39	40																								

		5 M. A.	10 M. A.	25 M. A.	50 M. A.	100 M. A.	150 M. A.	200 M. A.
X-RAY TUBE #	AMMETER READING							
X-RAY TUBE #	AMMETER READING							
X-RAY TUBE #	AMMETER READING							

NOTES—

1.—To insure satisfactory results with the above technique, your X-ray machine must first be accurately calibrated with a sphere gap.

2.—This technique is based upon variation of kilovoltage in accordance with thickness of part to be rayed. The part thickness should be accurately measured by means of a rule graduated in centimeters.

3.—When measuring the thickness of the part to be rayed, it is important to measure the thickest portion through which the central rays of the X-ray beam must pass.

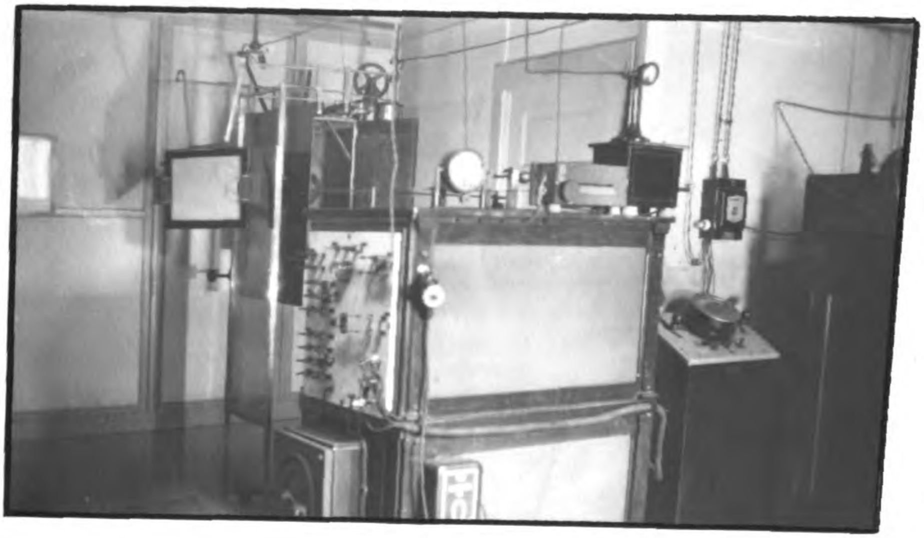
4.—The voltage indicated on the chart for a given thickness of part in centimeters is to be used for average patients. If the patient is very muscular, the next higher kilovoltage shown on the chart should be used.

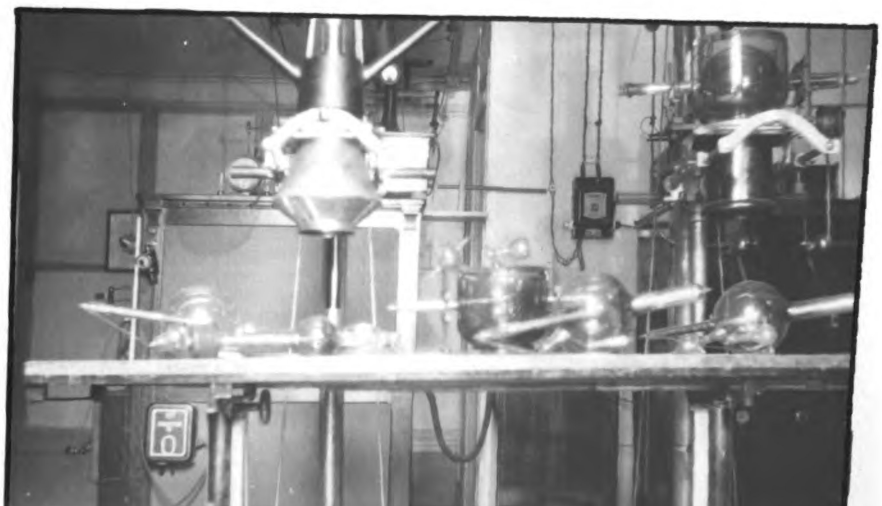
5.—As intensifying screens and films of different manufacturers vary greatly in speed, it is of the utmost importance to use this chart only with the combination of screens and films indicated at the upper left-hand corner. Should you change either films or screens, notify our office, and we shall be glad to mail you a corrected chart.

6.—Use a cone whenever possible. This will result in more brilliant radiographs.

7.—For all radiographs, an aluminum filter, either 1/2 m. m. or 1 m. m. thick, should be used.

8.—The correct time of development of films depends upon the temperature of the solutions. Follow the time-temperature chart supplied by the manufacturer of your films.





X-ray Laboratory

PART 11

KILOVOLTMETERS

1. Need for a Kilovoltmeter

As stated in the first page of this report a dependable kilovoltmeter is a most necessary part of an X-ray equipment. In the absence of such a device various other methods are now in use as substitutes. Among these are the following: The various intensity measuring devices, such as the ionization chamber and its associated system of "r" units; The cumbersome sphere gap; the various forms of electrostatic meters; and a voltmeter in the primary circuit of the high voltage transformer. In all of these it is necessary to have each machine calibrated by standardized instruments which have in turn been standardized with other machines. Thus it is often difficult if not impossible to repeat technique given in the literature under one of the methods of calibration, and there is thus no check on personal technique involved, as well as tube and operating characteristics. Above all, there is no meter indication of the instantaneous operation of the power plant and the wide fluctuations of the line voltage may throw a great error into the major part of the results. There is great need for a properly designed kilovoltmeter.

The importance of the kilovoltage factor in X-ray work is understood when it is known that the energy of the radiation is proportional to some power of the kilovoltage greater than two. In general practice, it is assumed to be the third power, in individual cases it may reach to the fourth or higher powers. The energy of X-rays is proportional to the first power of the milliamperes and time, the factors usually stressed and accurately measured. The energy is also inversely proportional to the square of the target-object distance.

In therapy work, both superficial and deep, slight variations in kilovoltage may mean the difference between a cure for the disease and the spread of the disease to other formerly healthy tissue, eventually causing the death of the patient. It is therefore justifiable that people have a wholesome fear of X-ray treatment, and resort to it only in preference to surgery.

Modern X-ray films have been developed with such a degree of latitude that wide variations of technique may be tolerated and still give a satisfactory radiograph. However, even this highly developed fool-proof film will not stand all kinds of abuse, and, especially in work with thick portions where contrast is necessarily small it is almost impossible to obtain good pictures unless the chart technique be followed closely. This assumes that all of the measurements are in correct units and not merely a rough calibration for a few reference points of the power plant controls, possibly by a doubtful method.

Precision laboratory work requires careful control and recording, and in much of the present day research work the kilovoltage must be determined and maintained with optical precision. The wave length measurements can only be relied upon when the direct current voltage applied to the X-ray tube is absolutely constant and known. Present methods do not allow that degree of certainty in the work.

Other work does not require such a finely calibrated instrument, but necessarily requires one with accuracy as great as the finest scale division. In this class is the use of X-rays for the promotion of biological processes and in metalurgical work for the examination of castings and welds. Crystalography and that division of metalurgy that is concerned with structure should use well designed kilovoltmeters in their diffraction apparatus both as an operation indicator and for the reproducing of experiments.

11. The Ideal Kilovoltmeter

In any form, the kilovoltmeter must be an accurate instrument, inasmuch as it is intended for use in laboratory work as a highly important trusted piece of apparatus. For the same reasons the instrument must be very reliable under all conceivable conditions of service to which it might possibly be subjected in use. This includes making the mechanical parts as nearly, "fool-proof", as possible. Because of the variety of service requirements met in practice the system must be sufficiently flexible to accommodate these widely different power sources. Where the X-ray tube is supplied with raw AC and serves as its own rectifier, a suitably designed potential transformer and voltmeter may be used. If the main transformer secondary resistance is high and considerable current is drawn, a correction should be introduced to cover the voltage loss in this secondary while current flows through the tube. The peak inverse voltage will always be higher than the peak forward voltage an amount equal to the loss in the transformer.

Closely allied with accuracy is readability. The instrument scale should be finely calibrated, preferably in one kilovolt steps. This would necessitate a scale with 250 divisions for an average instrument that would read to 250 kilovolts. This would also imply an accuracy of calibration of ¼%. Such an instrument would be ideal, but at present would be very difficult to construct and calibrate. However, with certain modifications an instrument might be constructed which would approach the ideal conditions. The simplest method is to make the instrument of multiple range, for example, 0 to 125 and 0 to 250 kilovolts. A more satisfactory set-up would be an arrangement to place the zero point off scale, and thus, with an instrument having 100 scale divisions, give a range of 50 to 150, and 150 to 250 kilovolts. Except for a few special cases potentials of less than 50 kilovolts are not used in X-ray work and the most useful radiographic range is from 50 to 150 kilovolts.

The kilovoltmeter should give a continuous indication and this requires the use of a standard meter style instrument. It should be dead beat with a short time constant so that instantaneous response may be obtained. This is necessary in view of the fact that many exposures are of the order of one second or less, and that the permissable time of operating the tube at high kilovoltage while making adjustments is quite limited.

Other requirements are that the instrument should be of such a size as to be more or less portable and sufficiently rugged to allow it to be carried from one laboratory to another without altering its calibration. The indicating instrument should operate at ground potential and the entire instrument should provide safety for the operator. The instrument should be sufficiently simple so that it may be duplicated in all laboratories at small cost. Such an instrument should be designed for ease of calibration, preferably without the use of another high voltage instrument. This calibration should be accurate for the smallest scale division and be permanent. This also implies that those instruments which use auxilliary sources of power should be independent of variations in the power supply.

The various instruments now available for this purpose fail in one or more respects to fulfill all of the requirements outlined above.

111. The Spark Gap

The point spark gap has been used to measure voltage in many X-ray laboratories and makes an effective display for spectators. However, it is almost worthless as a precision instrument. Quite as spectacular, but more valuable is the sphere gap. Large perfect spheres are used which are carefully polished and kept free from dust or any minute roughness. If the spheres have a radius greater than their distance apart they may be relied upon with fair accuracy. It is difficult to keep them in condition, and unless they are perfect, the results are considerably in error. Atmospheric conditions such as temperature, pressure and humidity cause variations and must be taken into account when making exact readings. Nearby electric fields also influence their behavior. The reading obtained is in peak kilovolts and gives no indication of the average value where pulsating D.C. is used. Resistors of high value are used in series with the spark gap to prevent an arc being struck when the spark passes which would ruin the sphere gap and cause a heavy and possibly dangerous current surge in the supply line.

Because of the disadvantages outlined above the sphere gap is not ordinarily used for routine work, but mainly to calibrate the control settings of machines which are then used blindly, assuming that the same transformer and resistance settings give the same

SPARKING POTENTIALS

(Peak Kilovolts)

Kilovolts	Needle points	5cm. spheres	10 cm. spheres	25 cm. spheres
10	....	0.29	0.30	0.32
15	1.30	0.44	0.46	0.48
20	1.75	0.60	0.62	0.64
25	2.20	0.77	0.78	0.81
30	2.96	0.94	0.95	0.98
35	3.20	1.12	1.12	1.15
40	3.81	1.30	1.29	1.32
45	4.49	1.50	1.47	1.49
50	5.20	1.71	1.65	1.66
60	6.81	2.17	2.02	2.01
70	8.81	2.68	2.42	2.37
80	....	3.26	2.84	2.74
90	....	3.94	3.28	3.11
100	....	4.77	3.75	3.49
110	....	5.79	4.25	3.88
120	....	....	4.78	4.28
130	....	....	5.35	4.69
140	....	....	5.97	5.10
150	....	....	6.64	5.52
160	....	....	7.37	5.95
170	....	....	8.16	6.39

Kilovolts	Needle points	5 cm. spheres	10 cm. spheres	25 cm. spheres
180	....	....	9.03	6.84
190	....	....	10.00	7.30
200	....	....	11.10	7.76
210	....	....	....	8.24
220	....	....	....	8.73
230	....	....	....	9.24
240	....	....	....	9.76
250	....	....	....	10.30

25° C. and 760 mm pressure.

From Kaye and Laby's "Physical Constants," Edition lV. As found in Robertson's "X-rays and X-ray Apparatus", p. 30

Temperature and Pressure Correction

Temp.	720 mm	740 mm	760 mm	780 mm
0°	1.04	1.06	1.09	1.12
10	1.00	1.02	1.05	1.08
20	0.96	0.99	1.02	1.04
30	0.93	0.96	0.98	1.01

Multiply kilovoltages by these constants for correction.

kilovoltage output. The sphere gaps are calibrated by x-ray wave length measurements or penetration photographs with specially designed instruments or by some form of ionization measurement. A table of commonly accepted relations between sphere gap sparking distances and kilovolts is shown on pages 48 and 49.

lV. Static Voltmeter

The static voltmeter has the advantage that it does not draw any power from the high voltage source. Different types possess various advantages and also serious disadvantages as outlined in section 3. The general type depends upon the attraction of the unlike charges for each other and may be read upon a suitable scale. A modified form consists of a small light sphere mounted on a bifillar suspension which is attracted to a second fixed sphere.

A radio vacuum tube may be operated with the grid as the anode and the plate as the control electrode, in which case the control is reversed and the system has an amplification factor of $1/u$, where $u =$ the amplification factor when the tube is used in conventional manner. If a tube were designed with the control electrode greatly separated from the other elements it might be used as a form of static voltmeter since the negative control electrode draws no current. Since glass has no effect on the direction and intensity of a static field the control electrode might be placed outside the glass envelope of the tube with equally good results, theoretically, and with a much smaller glass envelope. Accordingly a tube of the type -56 was built for this laboratory by the Sparks Withington Manufacturing Company which contained a heater-cathode and grid, but no plate. The heater was supplied with 2½ volts by a small transformer and the grid connected to the cathode through a milliammeter and a single dry cell. The cathode current was easily controlled by a 24 cm. ring placed around the tube and connected to the negative terminal of the X-ray machine. Difficulty was experienced by the steady collection of charges on the glass envelope of the tube from the air, and which quickly produced a field which masked the results of the external field. Further research might show a remedy for this difficulty. There is no discussion of this problem in available literature.

There is a force which tends to draw a body from a weak field to a point of stronger electric field provided that the body has a higher dielectric constant than the surrounding medium. Two semicircular plates were fastened to the ends of a bakelite rod and then suspended in suitable bearings. These were connected to the high voltage source and a pointer rigidly attached to the bakelite rod. The plates were so placed that they might rotate into a dish of transformer oil having a dielectric constant of 2.5. As electromotive force was applied to the plates they dipped more and more into the oil, the restoring force acting on the plates being the buoyant effect of the displaced oil on the plates. This is an improved form of electrostatic voltmeter, but it is subject to many of the disadvantages common to meters of this type.

Though justly considered a static voltmeter, a different form of instrument will be considered in section Vl.

V. Resistance - Milliammeter

The Taylor resistance system manufactured by the Shallcross Mfg. Co., forms an excellent voltage divider to be used with a sensitive meter or vacuum tube voltmeter, which is connected at the mid point and thus operated at ground potential. These non-inductive wire wound resistors may be measured and an instrument standardized by adapted laboratory methods may be designed.

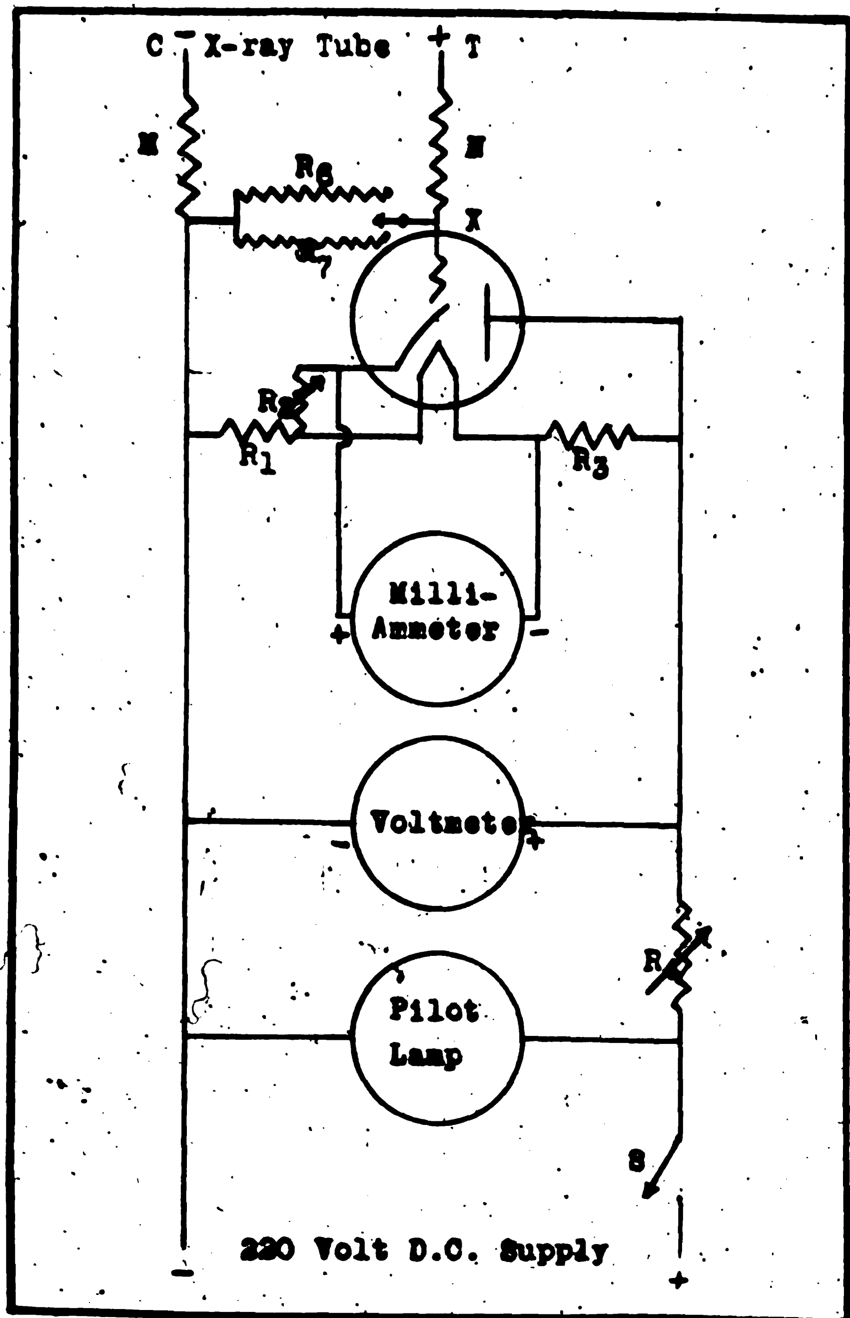
The disadvantages include the large amount of space occupied by the installation, the high cost, the considerable power consumption from the high voltage system, and the necessity for protecting the high resistance units from accidental personal contact. This installation might be practical in some special cases, but does not fit the needs of the average X-ray laboratory. Various materials such as high resistance liquids and composition mixtures have been used as voltage dividers, but they possess the additional disadvantage of lack of constancy with temperature, atmospheric and time changes, and vary with applied voltage rendering absolute calibration impossible. After a number of weeks of study and after conducting a number of preliminary tests with different forms of the electrostatic type devices, and after trying a number of different materials as resistances in the voltage divider type of meter it was decided to proceed with the design and construction of a kilovoltmeter based upon the general principle of the Voltage Divider in which a certain material called "wiroid" distributed by the Central Scientific Co. of Chicago and highly recommended by them would be used as the high resistance and a special form of vacuum tube voltmeter would be used as the voltage measuring device. The makers of "wiroid" claimed that the resistance remained constant for all allowable currents. Tests were made to ascertain to what extent the resistance of a sample of this material remained constant under varying conditions. The variation of the resistance of this sample with applied voltage is shown in the curve on page 73.

Because of corona and surface leakage it does not give especially good results, but as it is the best material so far tested in the reasonable price range it was decided to proceed with this material.

"Wiroid" is a flexible, slender, black filament closely resembling a "horsehair". It has approximately circular cross section and the resistance is uniform throughout its length, about 50 megohms per centimeter. About 36 feet of "wiroid" having a resistance of 50,000 megohms were wound in a spiral groove cut into a $1\frac{1}{2}$ inch bakelite tube 37 inches long, the thread rate of $2\frac{1}{2}$ threads to the inch giving the correct length of spiral. The "wiroid" is secured to the ends and connected to the supply wires by means of a small quantity of General Electric cement such as is used to connect the filament to the lead-in wires of the old carbon filament type lamps. At the electrical center of the

"wiroid" filament two flexible wires are cemented to the tube and carry the current passed by the "wiroid" to the vacuum tube voltmeter. The entire unit is covered with beeswax and inserted in a similiar bakelite tube with an inside diameter of 2 inches, as a protection for the delicate element from mechanical injury.

In connection with this research it was necessary to design a modified form of vacuum tube voltmeter to measure the voltage drop across the resistors that form the center portion of the voltage divider. The first unit to be constructed is shown on page 56.



Kilovoltmeter for Operation on 220 Volts.

Current from the positive line of the 220 volt D.C. supply passes through the switch S and thence to the small 220 volt pilot lamp L that indicates when the power is on, and prevents the meter from unintentionally being left on. A variable 150 ohm rheostat R_4 is used to regulate the voltage used in the voltmeter to 200 volts as shown by the voltmeter V, regardless of the main line voltage.

Both the plate and filament heater of the type -37 tube used in this voltmeter is supplied directly from this source, the 0.3 ampere current for the filament passing through the 621 ohm resistor R_3, the filament return to the negative line being through the 25 ohm resistor R_1. With a normal voltage of 200, there is a 6.3 volt drop across the tube heater, 7.5 volts across the 25 ohm resistor R_1, and 186.3 volts drop across the 621 ohm resistor R_3 with the normal current of 0.3 ampere.

In this vacuum tube voltmeter circuit the milliammeter is connected into the cathode side rather than the plate side of the tube circuit. The reason for this is to provide means for making the milliammeter read zero when no voltage is applied to the grid, even though the normal tube current of 0.004 ampere is flowing. This is accomplished in the following manner: The milliampere plate current in flowing through R_2 (1575 ohms) causes a voltage drop of exactly 6.3 volts across this resistor, the cathode connected side being of positive polarity with respect to the resistor. This is the same voltage drop that is experienced by the heater filament, the opposite terminal being positive with respect to the heater filament end of R_2. Thus there is no difference of potential between the cathode and the positive filament terminal, and hence no current flows through the milliammeter, even though there is a plate current of 4 milliamperes through the tube. Should the meter at any time give a reading when no potential is being applied to the grid, R_2 may be varied sufficiently to cause it to read zero. If a positive potential is now applied to the grid there will be a larger plate current, which, should it flow through R_2, would increase the potential drop through it. Instead, this current flows through the low resistance milliammeter to the positive filament terminal. Thus the plate current above 4 milliamperes flows through the milliammeter. The fall of potential across this instrument is negligible, being of the order of 10^{-3} volts.

When there is no voltage being measured, the grid is at the same potential as the negative line, being connected through the shunt resistors R_6 or R_7. Since there is no appreciable grid current the grid will remain at the same potential as the negative line unless an

external current is passed through the shunt resistors which would produce an IR drop, and thus change the grid potential. The cathode is at the same potential as the positive heater terminal, and is therefore positive with respect to the grid by the sum of the potential drops in the resistor R_1 and in the heater. The current is 0.3 ampere, and the resistance of R_1 is 25 ohms. The fall of potential across it is 7.5 volts. To this is added the 6.3 volt drop across the heater, making a total potential difference of 13.8 volts between the cathode and grid, the grid being on the negative side. This method of connection furnishes a fixed grid bias of -13.8 volts which is independent of plate current.

The plate voltage is the difference between the cathode potential and that of the positive 200 volt line, or 186.2 volts, which is not excessive for this type of tube. The maximum plate current is 10 milliamperes. The grid is so highly negative with respect to the cathode that it draws no appreciable current, and hence the device uses no power from the source to be measured.

In using this device as an X-ray kilovoltmeter points C and T represent the cathode and target ends of

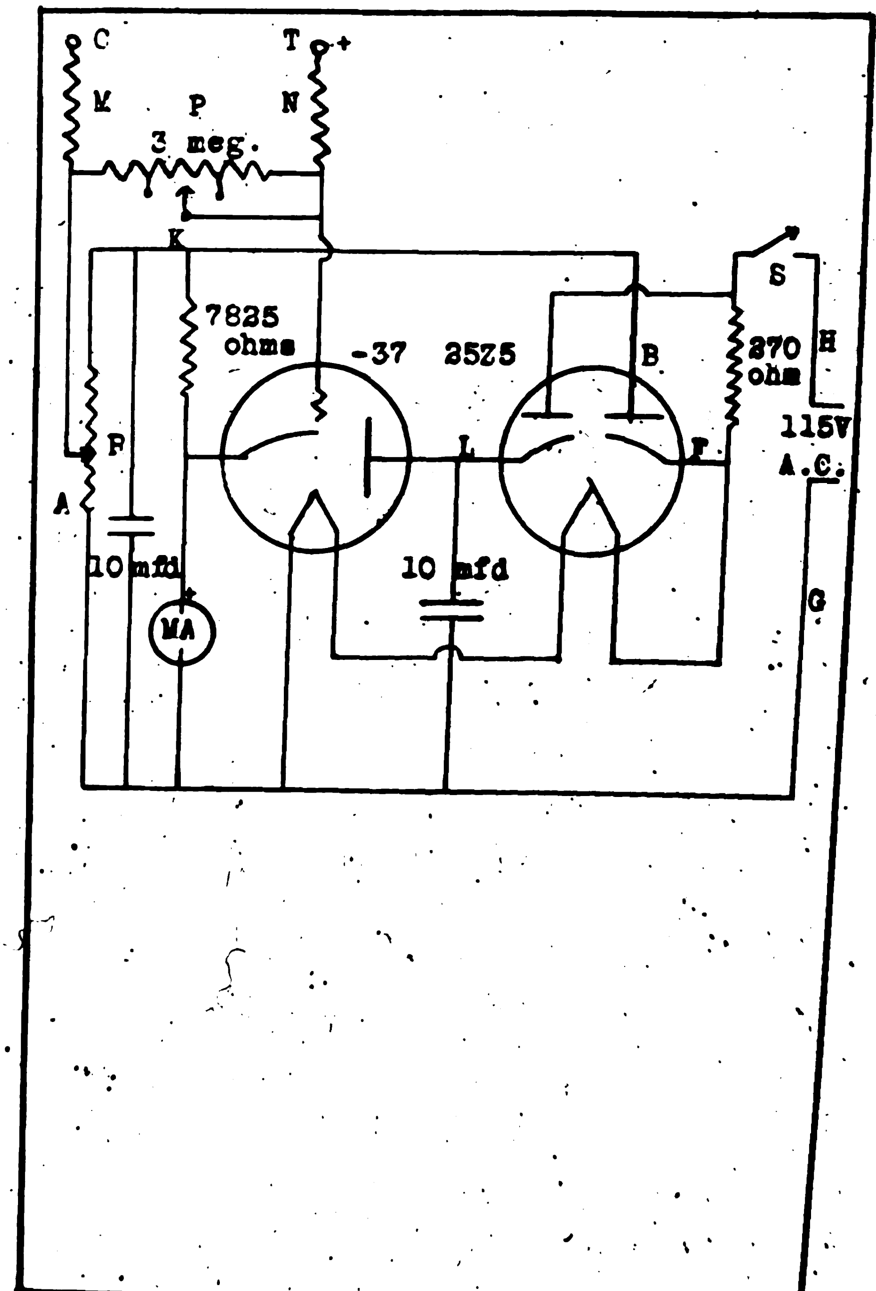
an X-ray tube, resistors M and N are the 18 ft. lengths of "wiroid" and the resistors R_6 and R_7 are the two resistors that form the central portion of the voltage divider, the potential drop across which is measured by the vacuum tube voltmeter. These resistors of different value give the instrument two ranges.

The potential drop in the resistors R_6 and R_7 is proportional to the kilovoltage applied to the ends of the "wiroid". Since the milliammeter reading is proportional to the voltage applied to the tube grid it is thus seen that the reading is proportional to the kilovoltage to be measured. The milliammeter scale may be calibrated to read directly in kilovolts or a calibration curve may be drawn showing the kilovoltage for various milliammeter readings.

On account of the fact that 230 volt D.C. sources of voltage are not common it was decided to build a vacuum tube voltmeter which would operate from the 115 volt 60 cycle A.C. lighting line and thus make a kilovoltmeter of more universal application. The circuit diagram for this is shown on page 63 and may be traced as follows: Starting with wire H of the 115 volt A.C. line the current passes through switch S and then through the 370 ohm resistor and then through the two tube filaments in series and out the other line G. This is permissible since the filament current of both tubes is 0.3 ampere. The use of transformers is in this manner avoided with a consequent saving in weight and cost.

The rectifier tube is the type 25-Z-5 and it is used as two half wave rectifiers in separate circuits. The left diode L is for the plate supply of the -37 tube and receives its potential directly from the line H. The cathode L is directly connected to the plate of the -37 tube and a 10 mfd condenser is used to smooth out the voltage ripple from the rectifier. The -37 cathode returns to the line G through the milliammeter.

The right unit R of the rectifier is used to furnish a fixed grid bias and also provide a means for causing the milliammeter to read zero when the normal plate current is flowing. The cathode is connected to one side of the filament at F and is thus at a potential of 6.3 + 25 = 31.3 volts R.M.S. above the line G. The movable arm A of the 5000 ohm potentiometer R is connected to the tube grid through the three megohm resistors and switch K, which is used to select the range to be used. Current from this same source B in passing through the 7825 ohm resistor is limited to 4 milliamperes, the normal



Kilovoltmeter for Operation from 115 Volts A,C.

plate current of the tube. Thus there is no current flow through the milliammeter when no potential is applied to the grid. This is maintained by the variable adjustment of resistor R.

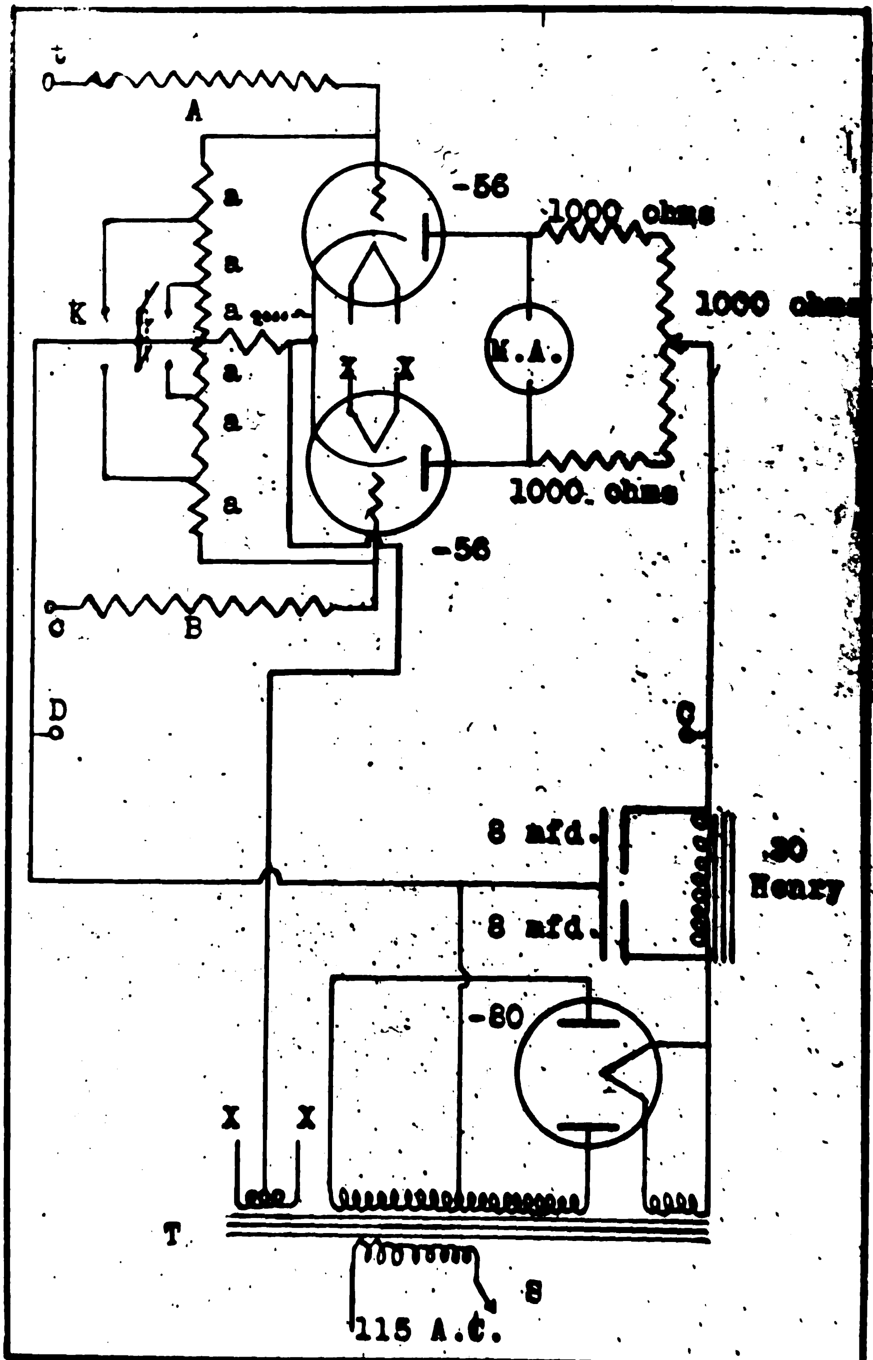
When a current passes through the three 1-megohm resistors a potential drop is produced across them and the grid is made more positive than it is normally and then a larger plate current flows. The first four milliamperes are supplied through the 7835 ohm resistor, and the rest passes through the milliammeter. It is thus seen that the reading of the milliammeter is directly proportional to the voltage impressed upon the grid of the tube. The current passed by the high resistance elements M.P.N. is proportional to the kilovoltage applied to C T. Thus the milliammeter reading is proportional to the kilovoltage, and a calibration curve may be drawn giving the kilovoltage for various milliammeter readings.

The vacuum tube voltmeter part is enclosed in a small metal case to shield it from the electrostatic fields when the high voltage is on. It has several openings for ventilation, which are covered with a fine mesh screen. It is mounted on short rubber knobs.

It was found that this circuit without modifications could not be used because the large fluctuations of the line voltage made a steady reading impossible. Accordingly another step in the evolution of this apparatus was undertaken and the circuit shown in the figure on page 66 was designed to eliminate these difficulties. The power supply is conventional, consisting of a transformer which supplies filament and plate voltage for the type 80 full wave rectifier tube. The filter circuit consists of two 8 mfd filter condensers and a 30 henry choke. No voltage divider is provided since the balanced tube circuit provides a constant load on the power supply. The high voltage is applied to the plates of the tubes through approximately 1500 ohms of resistance, which is adjustable for individual differences in tubes, so that the milliammeter may be made to read zero when no potential difference is being applied to the grids of the tubes. The milliammeter indicates the difference of plate current when a difference of potential is maintained across the grids of the tubes, and its reading is directly proportional to this difference of potential.

The tubes used are type -56, the heaters being supplied by the 2.5 volt winding of the power transformer. The center tap of this heater winding is connected to the two cathodes and the cathode current is supplied through a 2000 ohm self biasing resistor which gives the tubes the proper grid bias. No condenser is shunted across this resistor since the instrument is intended for D.C. voltage only. The grids are connected to ground through the resistors (a) which are each . 5 megohms, and which serve as the center leg of the voltage divider. These are so connected to a switch (K) as to give the instrument a multiple range. On the front panel of the instrument is mounted the line switch (S), range switch (K) and the milliammeter. The binding posts for the input from the high resistance units (A&B) are on the top of the case while the D.C. voltage test binding posts (C&D) are on the back of the case together with the AC line cord and plug. The entire instrument is contained in a sheet iron case which screens the circuit from electric and magnetic fields which are very strong in the presence of X-ray apparatus.

This instrument differs from an ordinary vacuum tube voltmeter in that it will only measure D.C. voltages. The power supply delivers current at 360 volts to the plates of the tubes. The plate current per tube is 5 milliamperes, and this current through the cathode self biasing resistor of 2000 ohms provides a grid bias of



Kilovoltmeter for Operation on 115 Volts A.C.

20 volts. By using identical tubes in this balanced circuit all disturbances due to the line voltage fluctuation affect each tube in the same manner and thus do not change the milliammeter reading.

The tubes, which are operated on the linear portion of their characteristic curve have their grids connected to the two wires from the high resistance units and thus when a current passes through the voltage divider the grid of one tube becomes more positive than normal and the other becomes more negative by an equal amount. Thus the plate current increase in the first tube just equals the plate current reduction in the second tube, and the combined plate current of the two tubes remains constant. This insures constant grid and plate voltage to the tubes. The tubes must be selected so as to have as nearly as possible identical characteristics, and in case of replacement should both be replaced with new identical tubes at the same time. A reproduction of a photograph of this instrument is shown on page 80.

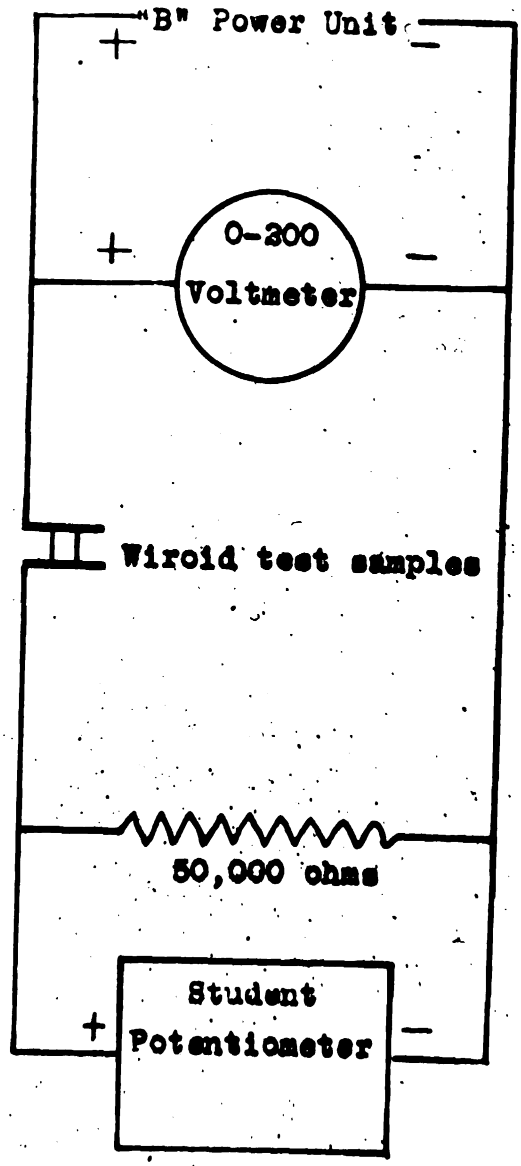
Calibration

The calibration of the instrument is done in two steps. First the high resistance wiroid elements are calibrated and then the vacuum tube voltmeter itself is calibrated, these two sets of data finally being combined to give the final instrument calibration.

The circuit used for the wiroid calibration is shown on page 70. A "G.M." power supply unit was used. Its controlled variable output was connected directly to a circuit consisting of two 1 cm. lengths of wiroid in parallel and these in series with a 50,000 ohm resistor. A voltmeter was also connected so as to indicate the voltage applied to this circuit. The voltage drop through the 50,000 ohm resistor for the various current values was measured with a student potentiometer. Two pieces of wiroid are used so as to give twice the current at a given voltage, and may be measured more readily. The results are given in the table on page 71, showing variation of the current with the applied voltage, and from this the resistance of the two wiroid filaments in parallel is calculated and shown in the third column. In the fourth column is indicated the percentage of the theoretical "no-current-resistance" that the wiroid has at the several current values.

I	II	III	IV
Volts	Current for each element microamperes	Resistance megohms	% of 0 current resistance %
0	0.0	(13.0)*	100
10	0.403	12.4	95.4
20	0.846	11.8	90.8
30	1.35	11.1	85.4
40	1.88	10.65	81.9
50	2.45	10.2	78.4
60	3.15	9.65	74.2
70	3.82	9.15	70.4
80	4.55	8.8	67.7
90	5.26	8.55	65.8
100	6.17	8.1	62.3
110	6.92	7.95	61.1
120	7.85	7.65	58.9
130	8.85	7.35	56.5
140	9.79	7.15	55.0
150	10.94	6.85	52.7
160	12.02	6.65	51.1
170	13.18	6.45	49.6
180	14.51	6.2	47.7
190	15.84	6.0	46.1
200	17.10	5.85	45. 0

*Estimated Graphically.

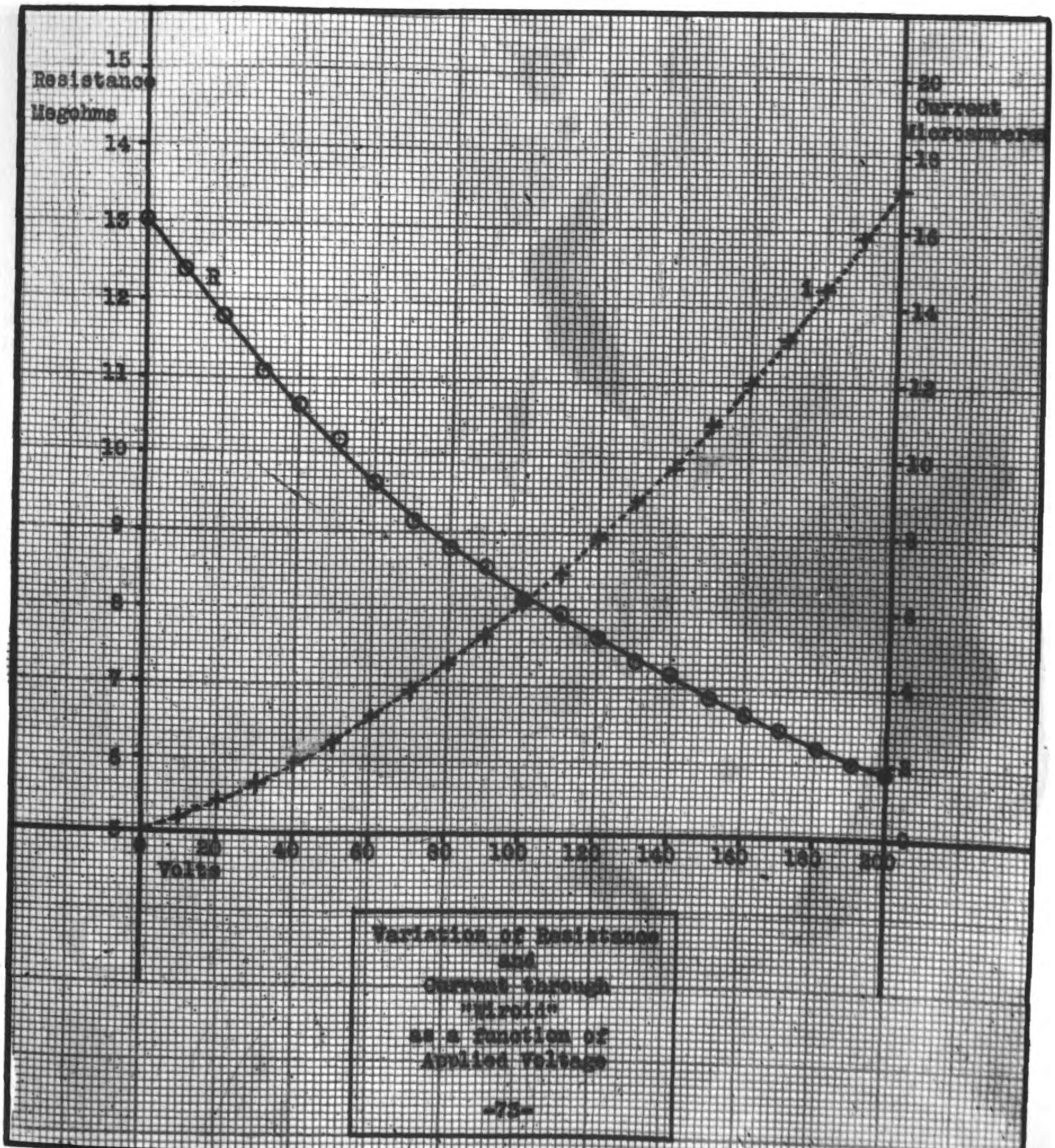


Calibration of Wiroid Resistance Units.

The voltage is increased in 10 volt steps and the current calculated from the relationship $i = e/r$ where e is the voltage as given by the potentiometer and r is the resistance of the unit across which this voltage is taken, in this case 50,000 ohms. The resistance of the wiroid part of the circuit would be equal to the voltmeter reading minus the potentiometer reading, divided by the current as found in column two. Since the voltage drop e through the 50,000 ohm unit is so small in comparison with the total voltage V no appreciable error is made by dividing the voltmeter reading V by the current i and thus obtaining the wiroid resistance. The curve shown on page 73 is then drawn, the absisca indicating the voltage and the ordinate the resistance of the wiroid. On the same graph is also plotted the current with respect to voltage and is shown as the dotted line. The graph is extended to form the intercept with the y axes which is a graphical determination of the "no-current-resistance". Column lV gives the percentage of this "no-current-resistance" of the wiroid at different values.

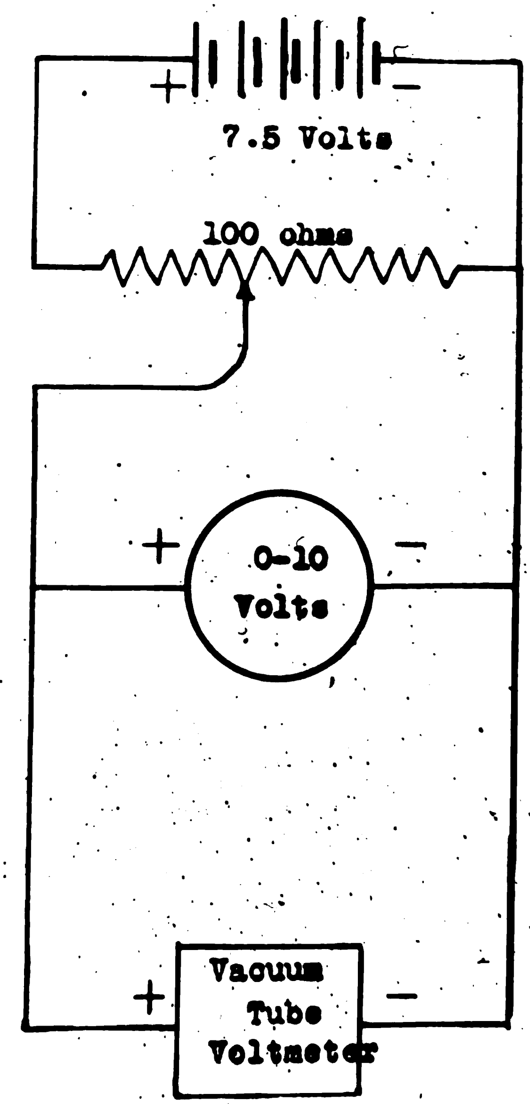
The resistance of the wiroid elements used in the voltage divider was found to be very nearly 50,000 megohms at zero current.

The circuit used in obtaining data tabulated on page 76 is shown on page 75. Here the vacuum tube voltmeter is supplied with known voltages from the small battery and potential divider, a high quality voltmeter being used to measure the several voltage values at which the vacuum tube voltmeter was calibrated. These are shown on column 11 of the tabulation. The position of the range switch is indicated in column 1. The total value of the shunt resistors for each range is given in column 111. The readings of the voltmeter corresponding to the milliammeter readings is given in column 1V. The current required to cause this deflection is given in column V, and is obtained by dividing the terminal voltage shown in column 1V by the value of the shunt resistor in each case as shown in column 111. For each current value shown in column V reference is made to the graph on page 73 and for each value of current the corresponding resistance value (solid curve) is found. The ratio of this resistance to the "no-current-resistance" of wiroid is given as a percentage in column V1. The value of the total high resistance in each case is then that percentage of 50,000 megohms and is given in column V11. The kilovoltage necessary



Variation of Resistance
and
Current through
"Wiroid"
as a function of
Applied Voltage

to give each meter deflection is the product of the current in column V and the resistance column V11, and is given in column V111. A calibration chart for the instrument is then made by recording separately columns 1,11, & V111. This is also plotted in the form of a graph on page 79.

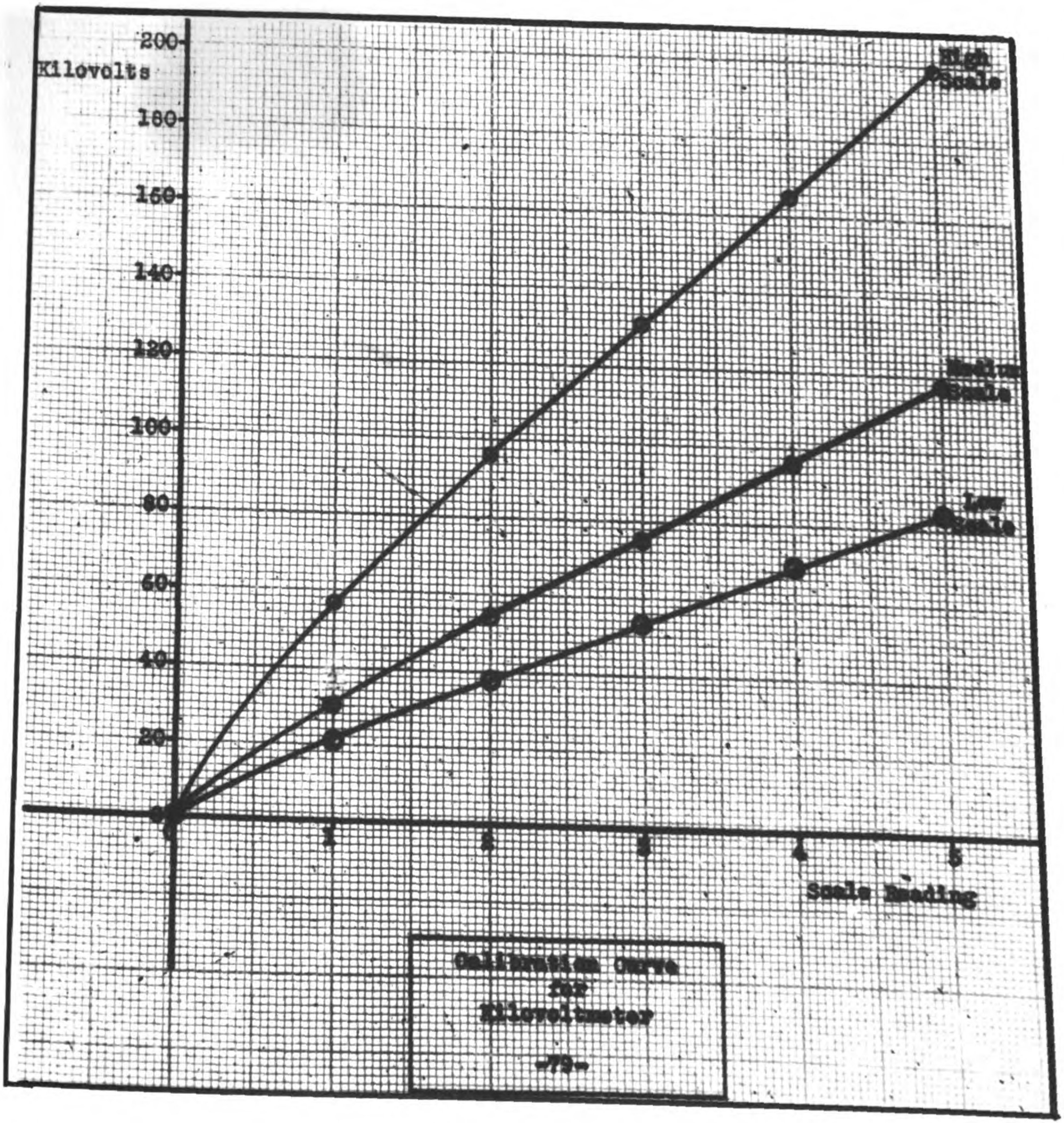


Calibration of the Vacuum Tube Voltmeter

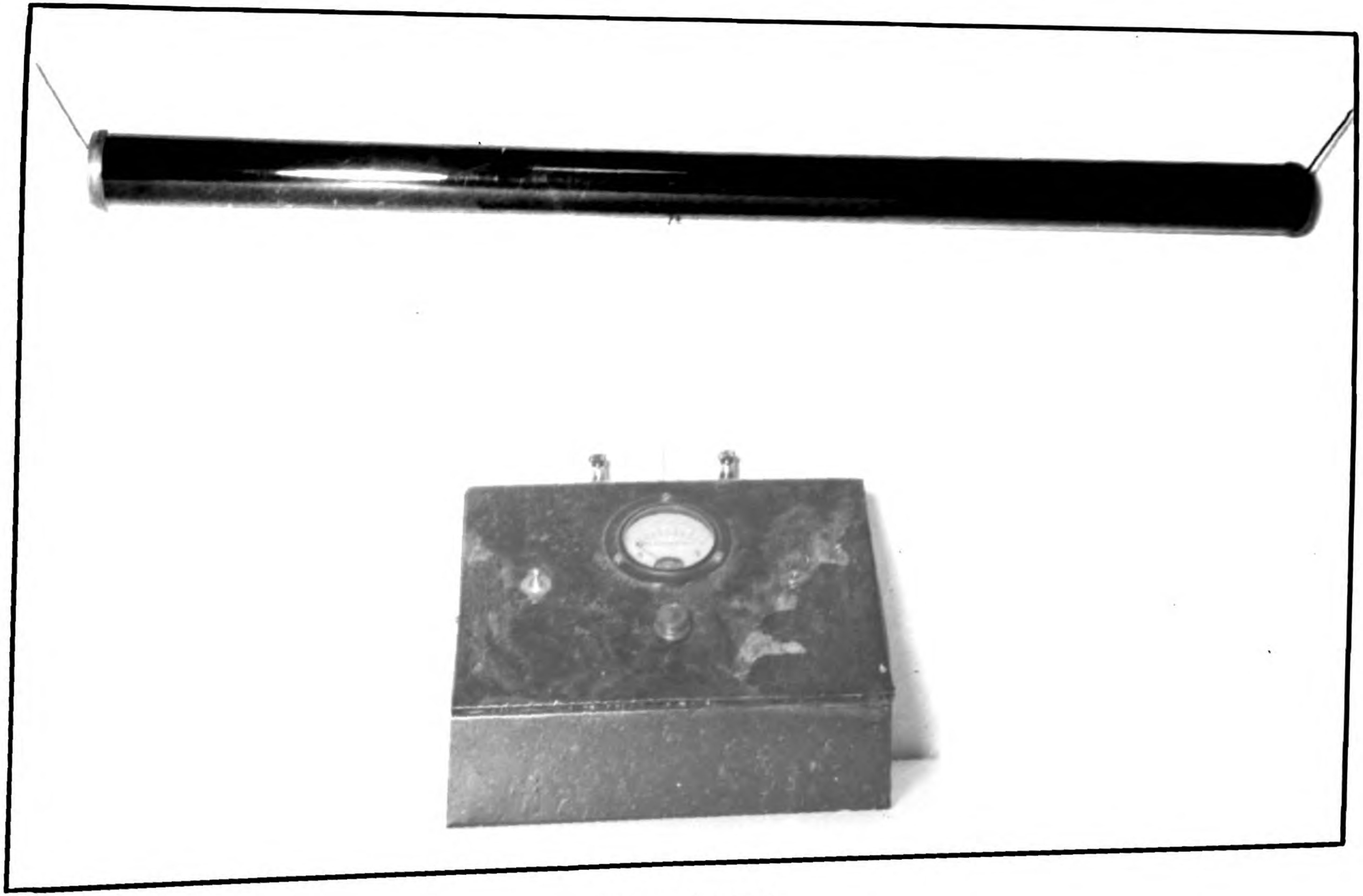
1	11	111	IV	V	V1	V11	V111
Range	Scale Read.	Res. Meg.	Volt	Current Microamp.	% total Res.	% of $5X10^4$ megohms	Kilovolts
Low	1	3	1.33	0.44	96.2	48,100	21.2
"	2	3	2.5	0.83	91.0	45,500	37.8
"	3	3	3.7	1.23	87.3	43,650	53.6
"	4	3	5.0	1.67	83.7	41,350	69.0
"	5	3	6.4	2.13	79.3	39,650	84.5
Med	1	2	1.33	0.66	93.0	46,500	30.7
"	2	2	2.5	1.25	87.1	43,550	54.4
"	3	2	3.7	1.85	81.3	40,650	75.1
"	4	2	5.0	2.50	77.3	38,650	96.6
"	5	2	6.4	3.20	73.3	36,650	117.2
High	1	1	1.33	1.32	85.9	42,950	56.6
"	2	1	2.5	2.50	77.3	38,650	96.6
"	3	1	3.7	3.70	70.8	35,400	131.0
"	4	1	5.0	5.00	66.1	33,050	165.3
"	5	1	6.4	6.40	62.3	31,150	199.2

Calibration Chart

Range	Reading	Kilovolts
Low	1	21.2
"	2	37.8
"	3	53.6
"	4	69.0
"	5	84.5
Med.	1	30.7
"	2	54.4
"	3	75.1
"	4	96.6
"	5	117.2
High	1	56.6
"	2	96.6
"	3	131.0
"	4	165.3
"	5	199.2



Calibration Curve
for
Kilovoltmeter

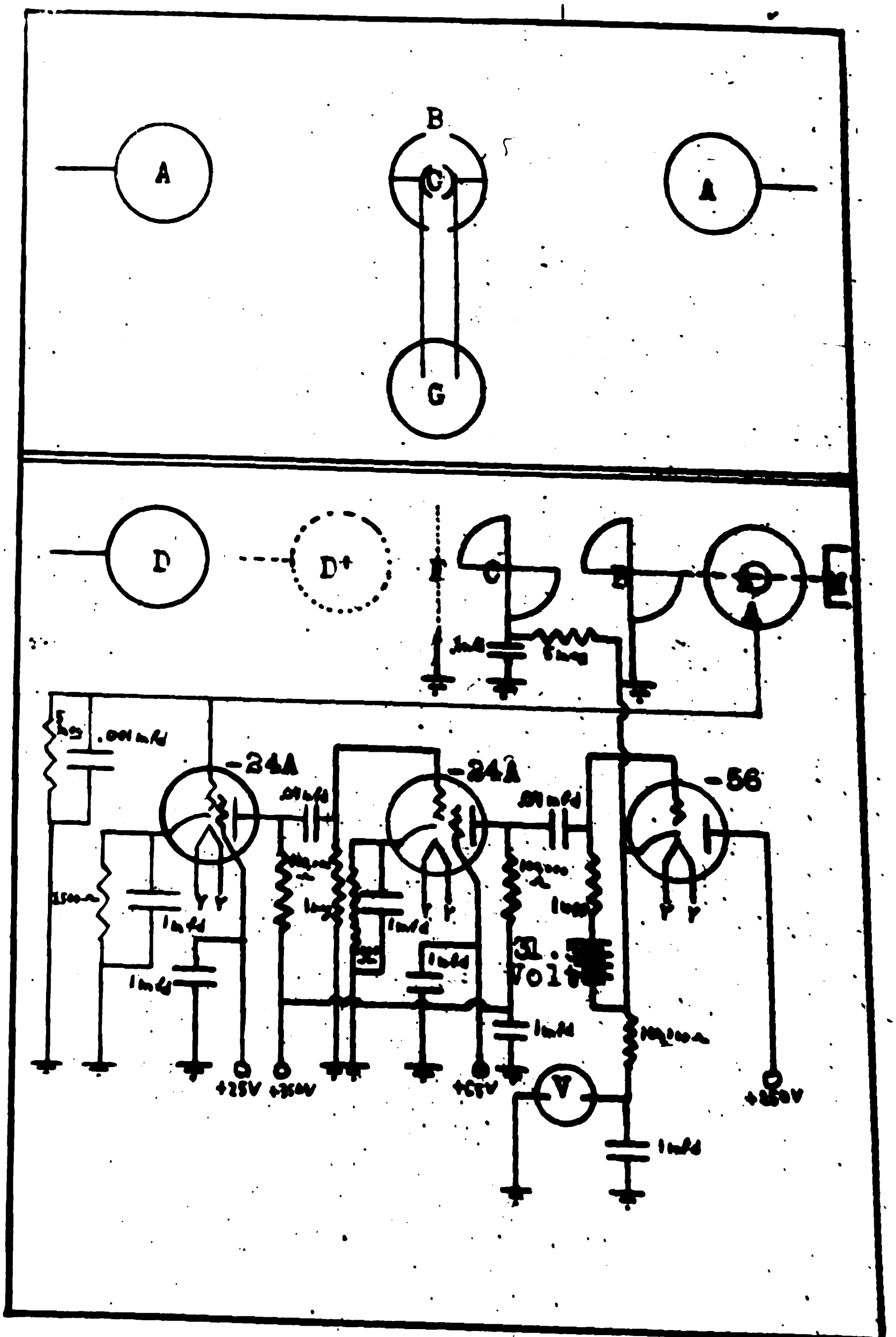


Kilovoltmeter

VI. Electrostatic Generating Voltmeter

The kilovoltmeter just described using the "Wiroid" resistance elements is subject to error which the calibration prodeedure given does not and cannot eliminate. Thus for final calibration it should be compared with a sphere gap which has been carefully calibrated. This error occurring when high voltages are used is due to surface and corona leakage from the wiroid resistance element to the air and through the insulating form.

An apparant solution to the problem of high direct current voltage measurement which satisfies nearly all of the requirements listed in section 11 is found in a modification of the apparatus designed by Kirkpatrick and Miyake and described in the review of Scientific Instruments 111, page 1. In general principle their apparatus shown in the upper figure on page 83 comprises two parts; a current generator consisting of a simple armature rotating in an electrostatic field, and a galvanometer for measuring the generated current. The electrostatic field is supplied by two spheres (A) connected to the high voltage source located a safe distance apart. The armature (B) consists of two insulated hemicylinders mounted on a synchronous motor shaft placed midway between the spheres and connected to



Generating Voltmeters

the wall type galvanometer through a simple commutator (C). This system is grounded for stability. It was calibrated by means of a sphere gap and checked by determining capicatance of the sphere-cylinder air dielectric condenser by measuring the area and distance apart, and substituting this computed value of C in the following equation:

$$Q = CV = it$$

$$V = \frac{t}{C} i$$

where t is determined by the speed of the motor and i is read on the sensitive galvanometer. V, the desired kilovoltage is then computed from the equation.

This was improved by Van Voorhis and Harnwell and described in the review of Scientific Instruments lV, page 540. Referring to the lower figure on page 82(A) is an insulated circular plate connected to the input of the vacuum tube amplifier. (B) is a revolving metal plate consisting of two grounded quarter segments and driven by a synchronous motor (M). (C) is a stationary insulated plate of two quarters, the same as (B). An open wire network grid (E) is placed in front of (C) and is grounded. This grid is used to reduce the effect of the high potential plate (D) which is connected to the positive high voltage terminal of the X-ray machine, the negative terminal of which is grounded. The grid is also used to assist in the calibration of the instrument. The amplifier and power supply are mounted in a grounded metal case, the plate (C) being in the plane of the front of the case.

In operation the plate (A) is alternately charged by induction when the plates (B) and (C) are in line and discharged the next instant when the plates are given a quarter turn. An alternating voltage is thus applied to the input tube of the amplifier, the frequency of which depends upon the speed of the driving motor, and the voltage of which is directly proportional to the potential of the plate (D). If (C) be now connected to some source of potential of the same sign as (D) the induced charge will not be entirely released at each cycle, and if the voltage of this plate is great enough, no alternating voltage will be fed into the amplifier. This voltage applied to (C) is automatically supplied by the rectified output of the amplifier and is measured by the voltmeter (V) which also is the indicating instrument.

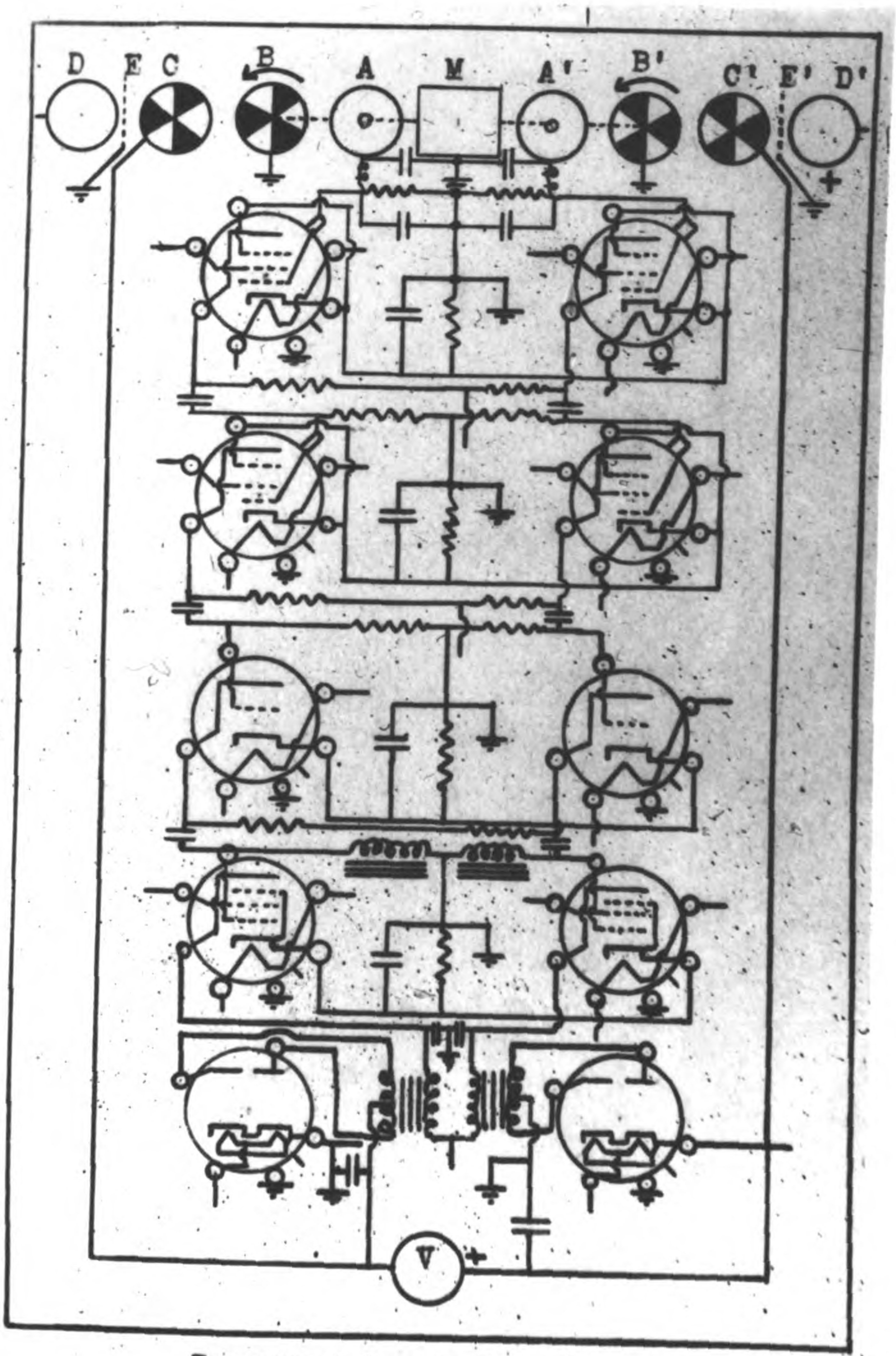
The amplifier contains two stages of resistance coupled amplification using type '24A screen grid tubes feeding a type 56 tube biased to plate current cut off, and which thus forms a detector or rectifier which supplies the direct current output. A conventional power supply system is used to supply the filament and plate voltages for the amplifier except for the grid bias for the rectifier which is obtained from a separate battery.

By using an amplifier with a high amplification it is possible to supply the high direct current voltage to (C) with negligible alternating voltage input from (A). Because of this, the difference between the reading given by the voltmeter and the actual voltage required to reduce the input voltage of the amplifier to zero may be neglected, and thus the instrument has a practically linear response.

The instrument is calibrated by placing the positive terminal of a fairly high voltage source of, for example 1000 volts D.C., which may be measured with a voltmeter, in front of the instrument as close as possible at position (D'). With the grid (E) removed a reading of 300 for example, near the maximum on the scale is taken. The grid (E) is then replaced and the reading, now only 10, is again taken. Dividing the 300 by the 10 gives the dividing factor of this grid, which in this case would be 30. Knowing this factor, it remains to remove (D') and connect various known direct current voltages to (D) with the grid removed, and plot a graph of the meter readings as a function of the products of known voltages and this grid factor. As an illustration let us say we connect the positive of a 1000 volt source to (D) with grid removed and we get a reading of 5 on our voltmeter. Since the factor of the grid is 20, a voltage of 20,000 volts attached to D would be expected to give a reading of only 5 on the voltmeter if the grid is in place. It can thus be seen that this grid factor may be regarded as a multiplying factor in that it makes possible the measurement of kilovoltages with a mere voltmeter. In use, the grid is always in its place, and the kilovoltage is found from the chart by comparing the meter readings with the voltage indicated by the graph.

This instrument gives very good results on a constant potential direct current system with the negative end grounded, but since most X-ray power units are not thus connected, a kilovoltmeter of this type is not, in its present forms, universal in application.

The proposed system shown in the figure on page 87 is designed to eliminate these difficulties and it is hoped that in the near future it may be set up and tried out. There are two sets of collecting plates so arranged that the instrument may be used where both power lines are at high potential with respect to ground, but would not interfere with the use of the instrument in a grounded



Proposed Generating Voltmeter

system, one half only being used. The plates (B & C) should have about 30 sectors instead of only 2 so that the frequency of the alternating voltage is near to 1000 cycles. This is suited to the needs of the amplifier and is handled more easily, and is sufficiently high to integrate the varying voltages as supplied by rectifier equipped machines, whereas a frequency of 60 as used in the original apparatus might be in step with some part of the cycle of machine operation and would only give the voltage at that part of the cycle. This might not include the peak and thus be in serious error, and there would be no way to correct for it.

Radio frequency chokes and grounded condensers protect the input of the amplifier from the radio-frequency currents which are common and of high value in systems using mechanical rectification. Small condensers are also placed at the output for the same reason. The amplifier should consist of separate balanced tubes in every stage so that line voltage fluctuation will have no extraneous effect on the operation of the amplifier. There are two stages of resistance coupled screen grid amplification, a stage of triode resistance coupled amplification, impedance coupled into the power output tubes in the fourth stage. Diode rectifiers are used in the last stage removing the necessity of a biasing battery and giving a more nearly linear output response. To this stage is connected the voltmeter and the plates (C & C'). The power supply is standard in every detail.

Multiple ranges might be had through the use of several grids (E) of different mesh, multiplication factor of each being determined as described above. These might be mechanically arranged so that each might be swung into place by setting a range knob on the control panel.

This seems to be the ultimate goal toward which the X-ray industry has been striving since the beginning of the use of high voltage apparatus.

Although no completely satisfactory method of measuring the kilovoltage applied to the terminals of an X-ray tube has been herein developed, a study of the methods in use at the present day has been made as well as an outline for future work in this field. It still remains the most perplexing problem of the Roentgenoligist to duplicate the technique and work of other laboratories when the kilovoltage is given, but without explanation of the devise used for that particular determination. The goal appears to be in sight and one may soon expect a really satisfactory instrument to be made commercially available. With it the control of X-rays will be complete, with their intensity, time of exposure, and wave length or penetrating power always at the will of the operator.

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