

## A NEW HIGH POTENTIAL X-RAY TUBE

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## ABSTRACT

An attempt has been made to develop apparatus and methods of operation for generating and investigating x-rays in the region beyond 300 kv. A tube is described which was designed to operate with 1000 kva, one million volt, transformers available at the California Institute of Technology. The tube is built up of glass cylinders internally shielded against electronic bombardment. The phenomenon of "cold emission" is utilized for obtaining the electrons, the full potential being applied between electrodes of suitable curvature placed close together, (1 to 2 cm). A preliminary report of the results is given. This includes oscillograms showing the peculiarities of the current due to "cold emission" as well as the actual potential across the tube. Absorption measurements of the x-rays have been made with lead up to 2 cm thick and it is shown that secondary emission plays an important part in the photo-chemical action of these rays. Satisfactory operation has been obtained up to 750 kv.

## INTRODUCTION

THE present paper is a preliminary report of the work done on the construction and operation of a high potential x-ray tube intended for investigating the radiation beyond about 300 kv.

Although no satisfactory quantitative analysis has as yet been completed we have thought it advisable to present the present paper at this time because one of us is leaving the Institute to take up other work elsewhere. It is expected, however, that the work will be continued here.

When this work was undertaken very little had been done to investigate the radiation produced by x-ray tubes at potentials above about 300 kv. Of the several reasons for this one of the most important is the expense and difficulty connected with the construction and maintenance of a satisfactory source of high potential. The apparatus necessarily becomes very large if one wishes to operate at commercial frequencies, not only because of insulation difficulties but also because great power is required merely to maintain the potential. Thus in the present apparatus the charging current at 750 kv amounts to 300 ma or 225 kva.

A second difficulty is the construction of the tube. If it is to be used in air it must be large to prevent external flash-over along the glass. Even if submerged in oil or otherwise protected it must be of large dimensions in order to maintain large clearance and large radii of curvature of the metal parts inside.

At sufficiently high potential gradient the metal parts give off an apparently unlimited supply of electrons and it is essential that these electrons be prevented from striking and puncturing the glass.

In the present tube this emission from the cold metals is utilized for producing the x-rays, no other source of electrons being required. The stray

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electrons are stopped by metal shields and conducted to ground by means of high resistance leaks shunted by suitable condensers.

The use of cold emission as a source of electrons in the production of x-rays has been attempted at lower potentials both in this laboratory and by Lilienfeld, but the operation has always been too erratic for practical use. At high potential this objection is not very important in the present instance.

#### EQUIPMENT AVAILABLE

The source of potential consists of the 1000 kv, 1000 kva transformer set of the California Institute of Technology, together with its control equipment. The set, designed by R. W. Sorensen,<sup>1</sup> consists of four units connected in cascade (see Fig. 1). Each unit has three windings. Two of these are rated

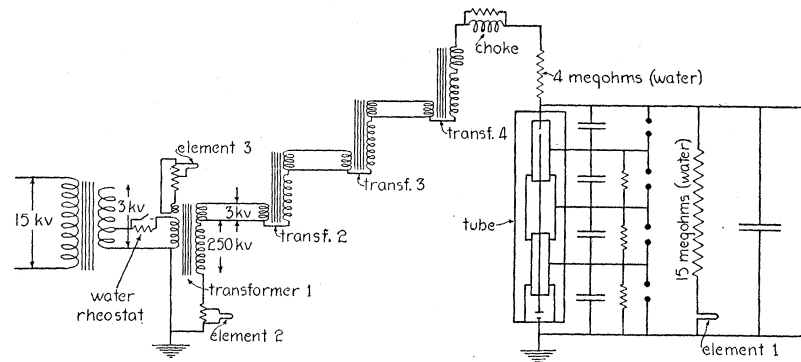


Fig. 1. Diagram of transformer set.

at 1000 kva at 3000 volts, one being connected to the case and the other insulated from core and case for 250 kv. Connected between these windings is the 250 kv winding. The case of each unit is insulated from ground for its respective potential.

This transformer set is housed in a room 64×138 by 50 ft high, the last three transformer with their insulating supports being placed in a pit in order to get sufficient overhead clearance.

#### THE TUBE

A sketch of the tube itself is given in Fig. 2. The supporting structure consists of a tower 14 ft. high and 8 ft. square at the base, constructed of red-wood timber crossed and braced to give rigidity. The bed plate of the tube consists of a piece of boiler plate 28×28×0.5 in. bolted to this platform. This plate has a hole 16 in. in diameter over which fits a water-cooled disk of 7/8 in. boiler plate making a foundation for the tube proper, and carrying the pump tubes and one of the water cooled electrodes.

The glass consists of cylinders each 12 in. in diameter and 28 in. long of the kind used in gasoline dispensing pumps. The lowest cylinder is set on a rubber gasket in a groove in the end plate and the other joints are made similarly in grooves in steel rings, leaks being prevented by coating the joints outside with

<sup>1</sup> R. W. Sorensen, *Journal A.I.E.E.* **44**, 373 (1925).

shellac after the tube is assembled. The steel rings also support the internal shields. These are of steel 1/16 in. thick alternately of 11 in. and 7 in. diameter overlapping about 4 in. at the ends. At each end of each shield is a ring of 1 in. diameter steel tubing to eliminate sharp edges. All joints are welded and carefully smoothed.

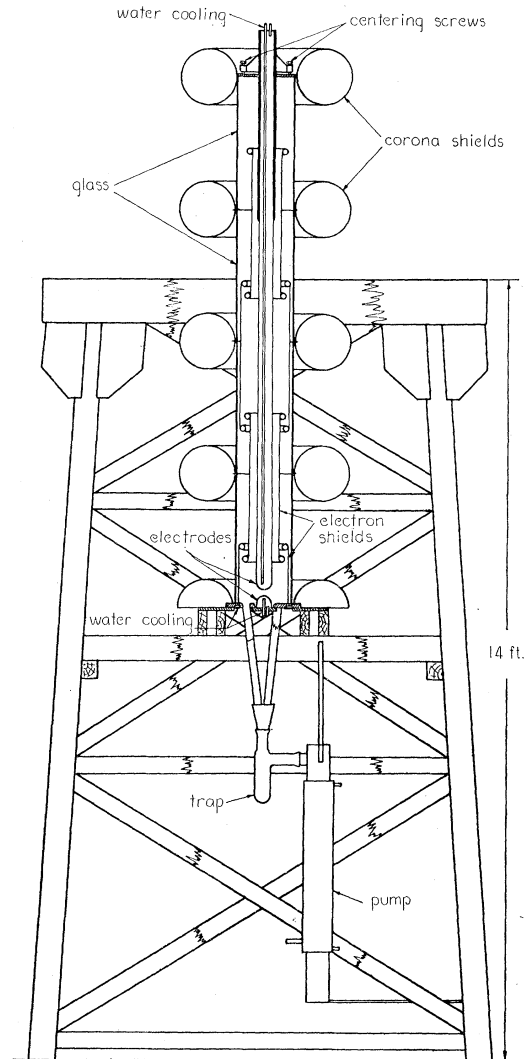


Fig. 2. Sketch of the tube.

The upper electrode consists of a three-inch diameter steel tube reaching to within four inches of the bed plate. The upper three feet of this tube has a 0.25 in. wall to give rigidity. It is supported in a circular cover plate of steel 0.5 in. thick with an arrangement of screws for flexing this plate in order to center the lower end of the electrode.

Each joint ring is equipped with an outside corona shield of tin foil covered papier-mache, in the shape of a torus whose circular section is one foot in diameter.

The lower end of the upper electrode has been given a variety of shapes including a steel cone with a rounded point, a three-inch steel hemisphere and the steel hemisphere equipped with points of steel and tungsten of various sizes. The lower electrode has had the form of a five-inch steel hemisphere concave upward, a flat plate of copper, with or without tungsten point, and a three-inch steel hemisphere convex upward. Both electrodes were water-cooled in all cases.

An idea of the form and position of the actual target for some of these electrode arrangements may be obtained from the pin-hole camera photographs, shown in Fig. 3.

#### CONTROLS

Power is supplied to the set of high potential transformers through induction regulators, the primaries of which are wound for 15,000 volts and the secondaries give any potential between 0 and 3000, the variation being continuous. These regulators and the necessary oil switches are normally controlled from either of two desks in the laboratory, but for the present experiment the controls have been extended to a service tunnel placing about six feet of concrete and several feet of earth between the operators and the tube, for protection against the radiation.

In the 3000 volt circuit is placed a water-break switch. This switch is so constructed that when open, it leaves sufficient resistance in the circuit to limit the potential on the tube to about 250 kv. When closed this resistance is cut out and the potential is raised to any chosen value. This arrangement removes the danger of destructive transients occurring in the transformers as a result of switching. The closing mechanism of the water-break switch is controlled through a contactor by a timing device by means of which it is possible to vary at will the number of closings per minute and the duration of each closing.

After the tube has been operated for some time it is possible to run it at high potential one second in eight, without raising the gas pressure beyond the capacity of the pumps or producing excessive heating of the electrodes.

#### PUMPS

The rough pump consists of a Cenco Megavac. Ahead of this are two stages of the usual size mercury diffusion pumps of glass. Next is a diffusion



Fig. 3. Pinhole camera pictures with various electrode arrangements.

pump built of steel with welded joints, having an annular nozzle 5 in. in diameter. A 2 in. side tube leads to the liquid air trap which is made of 3 in. diameter glass tubing. From the top of the trap three 1.5 in. diameter steel tubes connect to the lower end plate of the tube, the upper side of the holes being properly rounded and smoothed.

With this equipment it is possible to produce and maintain a pressure of less than  $10^{-5}$  mm of Hg, i.e. below the range of the McLeod gauge. That this pressure is sufficiently low for the present purpose is due to the fact that the electrodes are comparatively close together so that by far the greater number of electrons travel only a short distance and consequently have a correspondingly smaller chance to produce ionization.

#### PROTECTIVE RHEOSTAT

The tube is connected to the transformers through a protective rheostat having a resistance of about 4 megohms and consisting of 50 ft. of 0.5 in. hose hung in a spiral about a string of strain insulators. At each end of the spiral is a flat metal plate 6 ft. in diameter, this being necessary to equalize the field along the hose and prevent its destruction by corona. The metal plates are about 10 ft. apart, the upper one being some 20 ft. from the ceiling. Water to the rheostat flows up through a hose to the ceiling, then drops in a broken stream to a bucket on top of the upper plate, then through the rheostat hose and through the upper electrode of the tube from which it drops 20 ft. to the floor, the broken stream providing sufficient insulation.

#### MEASUREMENTS

*Potential measurements.* Several methods are available for measuring the potential actually applied to the tube, and several have been used with more or less success. By far the most satisfactory and illuminating for the present purpose is the record obtained by means of an oscillograph, as it gives not only the maximum potential, but also the rapid fluctuations characteristic of this particular method of operation. The oscillograph used is a three-element General Electric Type E-M Form C.

One of the oscillograph elements is connected between the high-potential end of the tube and the ground through a resistance of about 15 megohms. This resistance consists of about 75 ft of 3/8 in. diameter rubber tubing through which tap water is circulated.

A calibrated spark-gap is placed directly across the tube. This gap is usually set somewhat above the operating potential and thus serves as a limiting device.

A second element of the oscillograph is connected across a special winding on the core of the first transformer, thus recording the potential of this transformer which is quite accurately one-fourth of the total potential of the set.

In addition the first transformer is equipped with a device for measuring the charging current to the condenser bushing. This current is rectified by means of two small Tungar tubes and then measured on a d.c. milliammeter which is calibrated to read in volts directly.

*Current measurements.* Here again the oscillograph provides the most satisfactory method used so far. The third element of the oscillograph is connected directly in the ground return of the transformers and therefore gives a record of the total current, i.e. the charging current as well as the current through the tube.

*Radiation measurements.* Two methods have been used so far for investigating the radiation, namely, absorption of the x-rays in lead and absorption in aluminum of the secondary emission from lead.

Absorption measurements were made by covering a strip of a photographic plate by a block of lead having a wedge-shaped groove and exposing at a distance of about 30 cm from the center of the source. Simultaneously four other strips cut from the same plate and enclosed in lead of uniform thickness were exposed to the radiation at distances from 50 cm up to 8 m from the source.



Fig. 4. Absorption in lead wedge 1.5 cm to 3.7 cm in thickness.

Usually the blackening of at least three of these control plates would fall within the range of the main plate, so that calculations could be made assuming only the inverse square law of intensity.

The five plates were developed simultaneously and measured on a recording microphotometer, all five traces being put on the same record. From this record one can then measure directly that thickness of lead which has reduced the intensity to any desired fraction and thus obtain the necessary data for determining the absorption coefficient and wave-length. An example of such a plate is shown in Fig. 4.

In order to be able to load these plateholders in daylight the plates were wrapped in black paper. This wrapping was found to influence the blackening

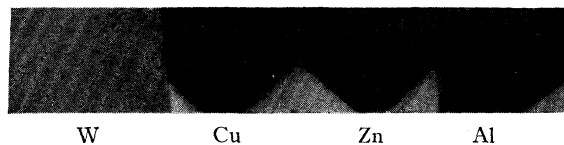


Fig. 5. Secondary emission from various elements behind 3 mm of lead.

to such an extent that one is forced to the conclusion that the photo-chemical action in the case of these hard x-rays is due primarily to secondary emission from the plateholder rather than to the direct action of the rays themselves.

In order to investigate this point the sensitive side of a photographic plate was covered with small pieces of various metals in the form of thin sheets and

then placed behind 3 mm of lead and exposed for about 30 seconds at a distance of 50 cm.

The blackening was found to increase greatly with the atomic number of the metal in contact with the emulsion, being very weak in the case of aluminum and very strong for lead. (See Fig. 5.)

The absorption in aluminum of the secondary emission from lead was shown by interposing a step-wedge made up of ten layers of 0.001 cm aluminum foil between the lead and the emulsion of the photographic plate.

The blackening of the plate decreases noticeably for each additional layer, all ten steps being plainly visible. This is shown in Fig. 6.



Pb

Fig. 6. Step wedge of Al each step being 0.001 mm.

It was found to be immaterial whether the sensitive side of the plate was turned toward or away from the tube.

A magnetic spectrograph for analysing this secondary emission has been set up but no results have been obtained up to this time.

#### OPERATION OF THE TUBE

The action of the tube seems to be somewhat as follows. The potential during any particular cycle builds up to a certain critical value at which a crater breaks in the negative electrode.<sup>2</sup> This crater then emits an unlimited number of electrons, amounting to a complete and exceedingly fast short circuit which not only reduces the potential at once to zero, but, because of the inertia of the circuit, actually reverses the potential across the tube. As soon as the potential can build up again the process is repeated, from one to fifty craters being broken during each half cycle. The critical potential and the asymmetry of the wave depend on the size, shape and materials of the electrodes and on how thoroughly they have become outgassed. Trace 1 on Fig. 7 shows a record of the potential across the tube.

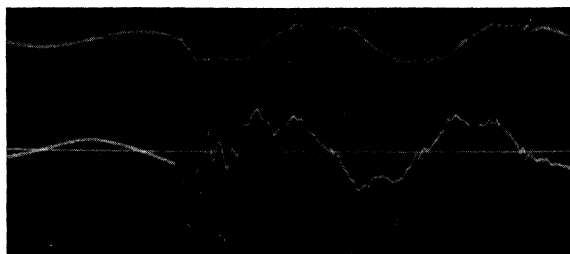


Fig. 7. Record of potential and current fluctuations.

<sup>2</sup> C. C. Lauritsen and R. A. Millikan, *Phys. Rev.* **31**, 914 (1928).

All attempts to obtain an oscillogram of the current directly through the tube with the instrument at hand were unsuccessful, the surges being too fast to be recorded, and too violent to be sufficiently reduced for the instrument by any reasonable amount of shunting. Apparently thousands of amperes are involved in these rushes of current, for a neon tube connected at both ends to the steel pump structure and laid alongside it still glows whenever a surge occurs. Consequently the oscillograph was put in the circuit at the low end of the transformers, the transformers, and the protective rheostat serving to limit the current in the surges. The resulting current is shown in the second trace of Fig. 7, the wave consisting of the electron current superimposed upon the charging current of about 300 ma necessary to maintain the potential of the transformers and connections.

#### CONCLUSION

So far satisfactory operation has been obtained up to 750 kv without outgassing the metals by any heating other than that incident to the operation. There is every reason to believe that the present limit is determined by the character of the electrodes and other metal parts of the tube and can be increased considerably by proper choice and treatment of these parts. The stray electrons can be rendered harmless by shielding, and the potential can be distributed between several sections by suitable capacities and leaks from the shields to the ground. By the use of fast pumps it is possible to produce a sufficiently good vacuum with the construction used. The radiation is very powerful and can be observed by means of a fluoroscope at a distance of 100 meters. Considerable blackening of a photographic plate is produced through 2 cm of lead. The photographic action is found to be due mostly to secondary emission which is strongly absorbed in aluminum.

In conclusion we wish to express our thanks to Dr. Millikan for his interest in the problem and for appropriating the necessary funds for carrying out the work and to Professor Sorensen for his cooperation and for putting the equipment of the high potential laboratory at our disposal. To Mr. Julius Pearson, chief instrument maker, is due our thanks for many helpful suggestions and valuable assistance in constructing the apparatus.

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August, 1928.



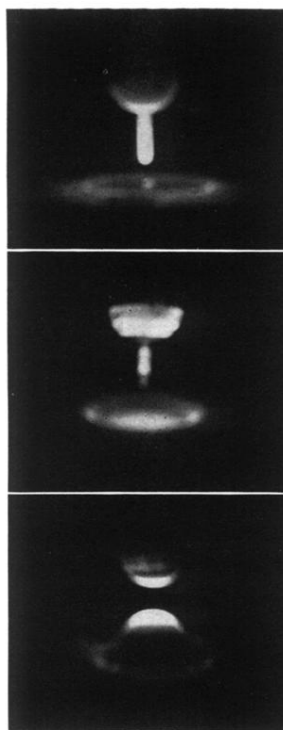


Fig. 3. Pinhole camera pictures with various electrode arrangements.



Fig. 4. Absorption in lead wedge 1.5 cm to 3.7 cm in thickness.

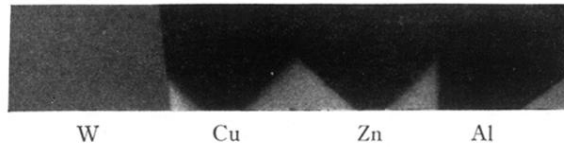


Fig. 5. Secondary emission from various elements behind 3 mm of lead.



Pb

Fig. 6. Step wedge of Al each step being 0.001 mm.

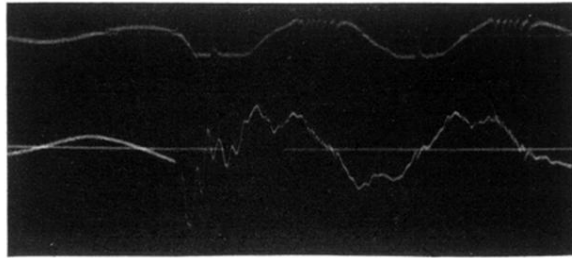


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