Experiments with a Condenser Discharge X-Ray Tube

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A condenser discharge x-ray tube is described from which it is possible to obtain a reproducible x-ray dose of 3.5 roentgens in about 5×10^{-6} sec. The current through the tube was of the order several hundred amperes. The effects of these high intensity x-ray pulses have been compared with the effects of x-rays of ordinary intensity from a Coolidge tube operated at a current of about 1 ma. The ordinary small chamber dosimeter was found to have a large recombination error for the high intensity pulses. The Bunsen-Roscoe reciprocity law was found to hold for the blackening of photographic plates, and for the coloration of crystals, by the high intensity pulses. Biological effects produced by the high intensity pulses in drosophila eggs, in the spores of aspergillus niger, and in wheat seedlings were found to be approximately the same as those produced by equal doses of x-rays of ordinary intensity.

UNDER certain conditions the discharge of a condenser between two electrodes in a moderately good vacuum gives appreciable x-ray emission. We have endeavored to obtain this phenomenon in a reproducible manner, and to make some experiments with the high intensity x-rays produced.

DESCRIPTION OF TUBE

The tube and circuit used in most of the work are shown in Fig. 1. A mercury pool was used ordinarily as cathode of the tube for the following reasons: (1) Running a low voltage arc (80 amp.) in mercury vapor provides an easy way of outgassing the anode. (2) No wall deposits are formed by evaporation of cathode material. (3) The pressure in the tube, and thus the peak discharge currents, may be controlled easily by varying the temperature of the mercury pool. In one experiment a cathode of tin was used instead of mercury; satisfactory x-ray emission was also obtained with this tube. The anode was always a tungsten disk, usually 4.5 cm in diameter. It was mounted with the center of its face about 7 cm from the surface of the pool, and somewhat out of line with the pool, so as to get as much current as possible to the face of the target. The anode was welded to a molybdenum support rod 3 mm in diameter.

DESCRIPTION OF CIRCUIT

The high voltage condenser was usually $0.025\mu f$, and could be charged to any desired voltage up to 140 kv. This voltage appeared across the spark gap shown, and when the gap broke down, part of the voltage was applied to the external starting band mounted close to the cathode surface. Without this starting band most of the tubes would not fire readily. Other methods of firing the tube were also tried, and the x-ray emission was found to be independent of the starting method. The main discharge current passed through the tube, only a negligible fraction going through the starting potentiometer. The loudness of the spark gave a rough idea of the magnitude of the discharge current.

CONDITIONS FOR SATISFACTORY X-RAY EMISSION

The x-ray emission occurs in the interval between the start of the discharge, and the change to a low voltage arc. Under suitable con-

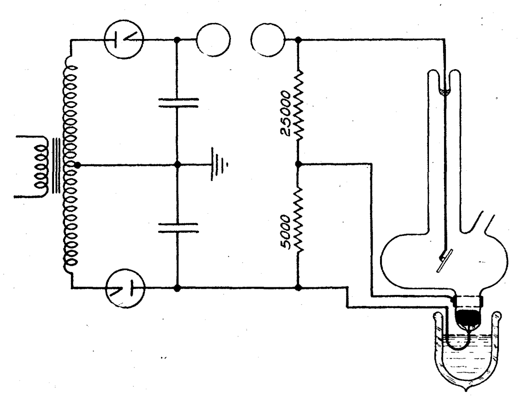

FIG. 1. Mercury pool x-ray tube and circuit.

ditions practically all the energy of the condenser can be used for x-ray emission, and none wasted in a low voltage arc. To secure this result the anode must be well outgassed. If the anode is gassy the electron bombardment is apparently able to produce positive ions at the anode, which are drawn rapidly to the cathode and eliminate space charge throughout the entire discharge path, so that very large electron currents can flow. Similar effects are produced by the presence of an easily vaporizable metal in the anode structure, or by close proximity of glass to parts of the anode. For such large and sudden currents an appreciable part of the voltage drop occurs in the inductance of the condenser leads, so that the x-ray emission is decreased.

There is also a limit to the capacity and voltage of the condenser which can be used satisfactorily. This limit is determined by two considerations. First, if it is attempted to pass too large a quantity of electricity through the tube in one "shot," the discharge will have time to change over to a low voltage arc, with a resulting decrease in the efficiency of x-ray production. Second, in these discharges energy is delivered to the surface of the anode at a tremendous rate, and if this is continued too long in one shot the surface of the anode is vaporized rapidly. Pin-hole camera pictures have shown that the discharge is usually distributed uniformly over the surface of the anode, so that the second restriction can be removed to some extent by increasing the size of the anode. Using a $0.025\mu f$ condenser charged to 105 kv, and a 4.5 cm diameter tungsten anode, we have passed many thousands of discharges through these tubes without any apparent vaporization of the anode, or any visible change in the tube except discoloration of the glass by x-rays and cathode rays (which can be removed by heating). On the other hand, the use of a $0.05\mu f$ condenser under conditions otherwise the same, gave appreciable vaporization of the anode in a few hundred shots.

The cleanliness of the cathode pool is apparently unimportant in determining the x-ray emission.

Measurement of X-Ray Output

The earlier measurements were made with a Leybold fiber electrometer and ionization chamber (3×4.5 cm) placed 70 cm from the target. Later measurements were made with a standard Victoreen dosimeter.

Effect of Mercury Pool Temperature on Peak Current and X-Ray Output

The peak currents were measured by putting a wire resistance (5.4 ohms) in series with the tube, and measuring the peak voltage drop across this resistance with a spark gap exposed to the light of the main spark. The arrangement was calibrated by replacing the tube with a 105 ohm noninductive resistance, and measuring the peak voltages across several wires of different dimensions but all of 5.4 ohms resistance. The effect of the different inductances of these wires was evident in these calibrating measurements. On the other hand, all the wires gave substantially the same result when used to measure the current through the tube. From this it was concluded that the current through the tube built up slowly enough to use simply the ohmic resistances of the wires in calculating the peak current.

Some measurements of peak current as a function of cathode temperature are shown in Fig. 2. The upper current curve was taken when the tube was in such condition as to give fairly rapid breakdown (large currents, and loud sparks). The lower curve represents the usual stable state of the tube. In both cases over the range of cathode temperatures from $-50°$ to $-5°C$ the peak current is nearly independent of the temperature. This means that in this range the initial vapor pressure of mercury in the tube is not high enough to supply an appreciable amount of ionization for the neutralization of electron space charge. The ionizable vapor presumably comes from the cathode spot on the cathode surface, and if this is so there must be a time interval between the formation of a low current cathode spot, and the building up of a high current, sufficiently long to allow vapor from the cathode to reach the neighborhood of the anode. The ionizable vapor in normal operation of the tube cannot be tungsten vapor from the anode because this would blacken the tube readily, whereas actually many thousands of discharges

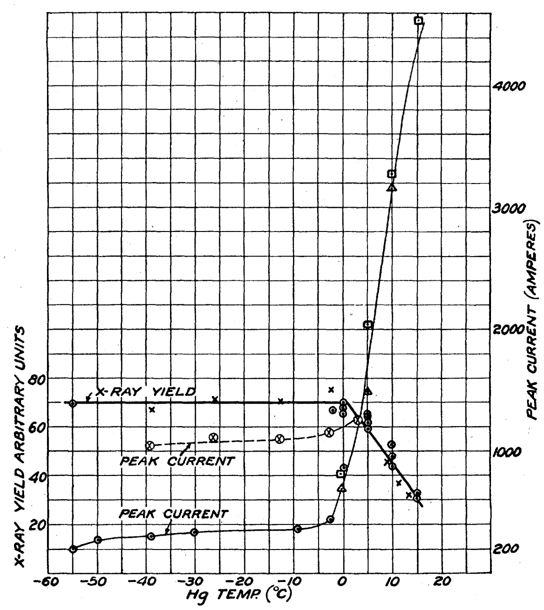

FIG. 2. Effect of temperature of mercury pool on peak current and x-ray yield.

can be passed without any visible evaporation of tungsten.

At cathode temperatures above 0°C the peak current rises rapidly, because the initial presure of mercury vapor in the tube is sufficient to give a substantial reduction of space charge throughout the discharge path. In addition, at the larger peak currents (2000 amp.) the supply of energy to the surface of the tungsten anode (4.5 cm diameter) is so rapid that appreciable evaporation of tungsten occurs after a few hundred discharges.

Figure 2 also shows the x-ray yield per shot as a function of cathode temperature. It will be seen that this is strictly independent of temperature and peak current up to 0°C, but then falls to half-value at about 13°C. The total x-ray yield per shot, of course, is independent of the rate at which electricity is taken out of the condenser. The decrease in output at large currents is due to the voltage drop occurring in the circuit leads (about 5 meters of copper strip 2.5×0.063 cm). If a smaller, stiffer circuit were used, presumably the x-ray yield would be maintained at larger currents.

Measurement of Duration of X-Ray Emission with Moving Photographic Film

Four dental films were mounted on a Duralumin disk and rotated at such a speed that the film moved 1 mm in 12.8×10^{-6} sec. Between the rotating disk and the tube was placed a fixed slit 1 mm wide. Single shot exposures were made first with the film stationary, and then with it moving. Fig. 3 shows a microphotometer record of such a film. At half the height of the peak the moving film image is 0.3 mm wider than the stationary film image, indicating that the x-ray emission lasted 4×10^{-6} sec. In this experiment the charge in the condenser was 2×10^{-3} coulomb, so that an average current of 500 amp. would discharge it in 4×10^{-6} sec. The photographic and peak current measurements are therefore in agreement as to the order of magnitude of the currents involved.

X-Ray Output as Function of Voltage

Figure 4 shows x-ray output per shot as a function of condenser voltage (0.025μf). The output was measured with the 3×4.5 cm ionization chamber placed 70 cm from the target. The circles in the figure refer to the mercury pool tube, while the crosses in the figure are measurements for the same condenser discharged through a standard Coolidge x-ray tube (2×10^{-3} amp. current). The glass of the mercury pool tube was Nonex, 2.4 mm thick. As Nonex glass contains a considerable amount of lead, an equal thickness of Nonex glass was placed in front of the thin-walled bulb of the Coolidge tube before making the measurement. The x-ray output is evidently about the same for equal quantities of electricity discharged through either tube, irrespective of the rate, the agreement being as good as could be expected when one remembers that there was a considerable amount of radiation from the backs of both targets.

The mercury pool tube used for these measurements had a target 4.5 cm diameter. If a target 1.8 cm in diameter was used, the output did not increase much above 100 kv, because there was so much evaporation of tungsten from the small anode that the discharge current built up rapidly to a higher value than the circuit could supply without voltage drop in the leads. Evidently the maximum output obtainable increases with the size of the anode.

Quality of X-Radiation

The quality was measured by absorption in copper. It was found to be roughly the same as that of the radiation obtained when the same condenser was discharged through a standard Coolidge tube.

Absolute Measurements of X-Ray Output

These measurements were made with a Victoreen dosimeter placed at different distances from the target. Two ionization chambers were used: a large one 1.14 cm internal diameter $\times$ 2.3 cm long, and a small one 0.77 $\times$ 1.3 cm. The axial collecting wires in both chambers were 0.75 mm diameter (data from Mr. J. A. Victoreen). The initial voltage on the collecting wires is about 400. Fig. 5 shows data taken with the mercury pool tube and a Coolidge tube plotted in such a way as to exhibit the inverse square law. All the data were taken with the condenser charged to 105 kv. The glass of the mercury pool tube was

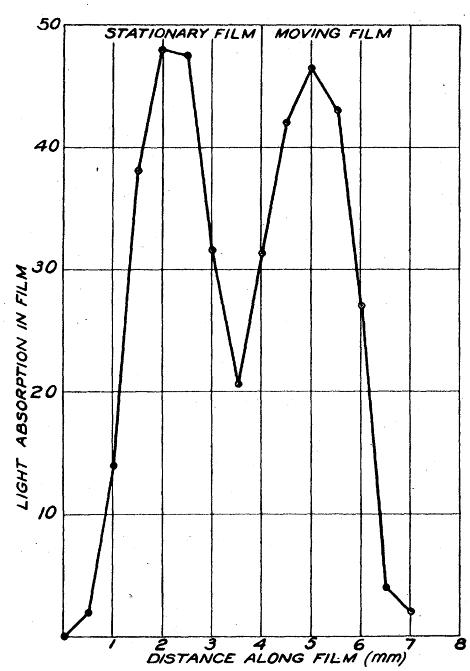

FIG. 3. Microphotometer measurements of x-ray image of a slit on stationary and moving films.

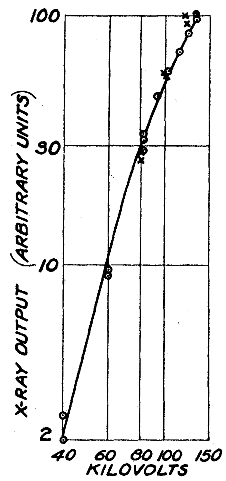

FIG. 4. X-ray output as a function of condenser voltage. The circles refer to a mercury pool tube, and the crosses to a standard Coolidge tube.

1 mm thick, and contained no lead. No additional filter was used with either tube.

Curves C and E were taken with the Coolidge tube and 0.025 and 0.05μf, respectively. The large chamber was used for the measurements. Curves A and B were taken with the Hg pool tube, 0.025μf and the small and large chambers, respectively. Both curves coincide with curve C for the Coolidge tube at large distances (small $1/d^2$), but diverge from C at small distances. This divergence is greater for the large chamber (B), hence it is presumably due to recombination of ions in the chamber. The electric field sweeping out the ions in one of these chambers is of the order 1000 volts/cm. The gas in the chambers is air at atmospheric pressure, so that the mobility of the ions is about 1.3 cm/sec. per volt/cm, and an ion will require several hundred microseconds to cross the chamber. The x-ray output for one shot is delivered in about 5 microsec., so that the entire ionization due to one shot is concentrated in the chamber at one time. Lack of saturation sets in for the large chamber at about 0.5 r per shot, and for the small chamber at about 1.1 r per shot. The ion concentrations corresponding to these doses may be obtained by dividing by the charge on the electron (in e.s.u.) and are 1.05×10^{10} and 2.3×10^{10}. These concentrations are so high that the lack of saturation is not surprising.

Curve D was taken with the mercury pool tube and $0.05\mu f$, using the small chamber. This curve shows lack of saturation also at small distances. Note that at large distances the output is the same as for the Coolidge tube (curve E), and is approximately twice that obtained with the $0.025\mu f$ condenser.

In all experiments with the mercury tube in which the object was placed close to the tube, the dose was determined from the inverse square law, as in curve C. Thus for an object placed 11.5 cm from the target and irradiated with the $0.025\mu f$ condenser charged to 105 kv the dose per shot was taken to be 3.5 roentgens. Assuming this dose to be delivered in 5×10^{-6} sec., the momentary rate was 4.2×10^{7} r/min. By increasing the size of the anode, and raising the voltage to about 300 kv, it would appear that doses of 30 r per shot could be delivered.

The maximum average output of the tube depends on the maximum heat dissipation of the anode. In our tubes there was no cooling except by radiation. The tube was usually operated at 105 kv, $0.025\mu f$, and 1 shot per sec., giving an average output of about 200 r/min. Under these conditions the anode ran yellow.

Photographic Effect

The density of an exposed photographic plate is defined as the $\log_{10}$ of the ratio of the transmitted to the incident light, and is usually taken to be a measure of the amount of x-radiation acting on the plate. Bell[1] and others have shown that at ordinary x-ray intensities the reciprocity law holds; that is, that the density is equal to the intensity$\times$the time of exposure. It was of interest to see whether the reciprocity law extends to the high intensities used in this work.

One-half of a dental x-ray film was exposed to one shot at 100 kv from the mercury pool tube, the film being placed at such a distance that it received 0.31 r. The other half of the same film was then exposed to as nearly as possible the same dose from the same condenser discharged through a Coolidge tube (10^{-3} amp. current). The film was then developed and photometered. The measurements on four such films (2 in each film-pack) are shown in Table I. The instantaneous rate of dose was about $0.31\times60/5\times10^{-6}$ $=3.7\times10^{6}$ r/min., and the data show that the reciprocity law holds to within 10 percent at this intensity.

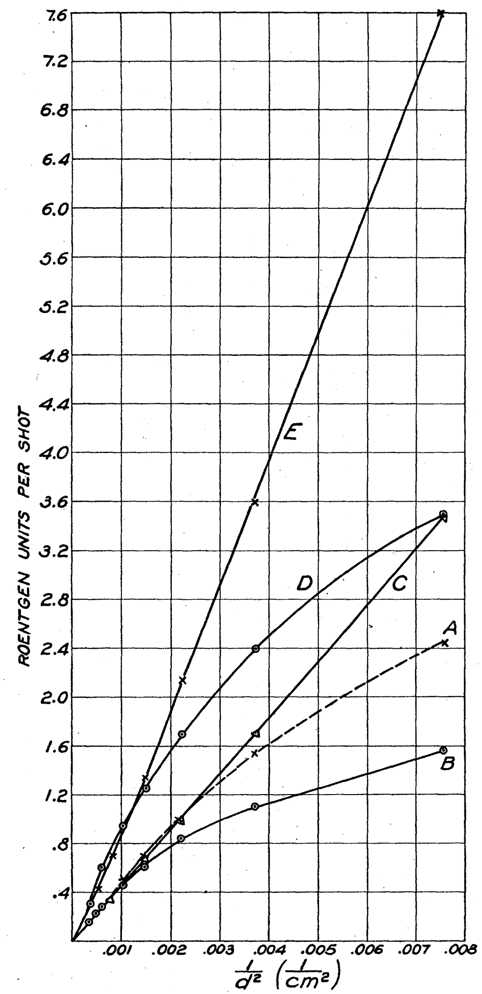

FIG. 5. Absolute x-ray output of Coolidge and mercury pool tubes, plotted to exhibit inverse square law. All 105 kv. A, Hg pool, $0.025\mu f$, small dosimeter chamber; B, Hg pool, $0.025\mu f$, large chamber; C, Coolidge, $0.025\mu f$, large chamber; D, Hg pool, $0.05\mu f$, small chamber; E, Coolidge, $0.05\mu f$, large chamber.

Coloration of Crystals

Single crystals of NaCl and KCl were exposed to the radiation from the mercury pool tube. The condenser was charged to 105 kv, and the crystals received 3.4 r per shot. A total dose of 340 r gave strong coloration of the crystals. The experiment was repeated discharging the con-

[1] G. E. Bell, Brit. J. Radiology 9, 578 (1936).

denser through a Coolidge tube instead. The coloration of the crystals was roughly the same in both cases.

Biological Effects

Experiments have been reported by Lawrence, Zirkle and their associates[2] in which it has been found that a given dose of neutrons, as measured by the ionization in a Victoreen dosimeter, produces a larger biological effect than an equal dose of x-rays measured by the same instrument. The greater efficiency of the neutron radiation is thought to be connected with the higher concentration of ionization along the path of a recoil proton than along the path of an electron ejected by the x-rays. It therefore seemed worth while to make some simple biological experiments with the mercury pool x-ray tube to see whether the high instantaneous concentrations of ions produced by it in tissue would cause any effects different from those produced by x-rays of ordinary intensity. We made some measurements on wheat seeds, and, with the collaboration of P. A. Zahl and C. P. Haskins (of the Haskins Laboratory, Union College) on drosophila eggs, and on the spores of aspergillus niger (bread mold). These experiments will be described in detail elsewhere, but the result may perhaps be mentioned here, and its physical interpretation discussed.

For none of the three materials investigated was there any significant difference between the effects of a given dose of radiation from the mercury pool tube, and the same dose from a Coolidge tube operated at a current of about 1 ma. The intensity of radiation during the momentary pulses from the mercury pool tube was about 10^5 times that of the Coolidge tube.

The significance of the experiments may be understood better by considering in detail the concentration of ionization[3] along the paths of an electron and a proton.

Cloud chamber photographs[4] have shown that about half of the ion pairs produced by a high speed electron (25 kv) are primary ionizations by the high speed electron itself, while the other half of the ion pairs are due to secondary ionization by primaries of moderate speed. Wilson's data are compiled in Table II.

For the protons, about $\frac{1}{4}$ of the ion pairs are due to primary ionization by the proton, the other $\frac{3}{4}$ being produced by ejected electrons of moderate speed.

These ionization data are illustrated in Fig. 6 for a 3×10^4 volt electron (two upper lines in series) and for a 3×10^5 volt proton (lowest line). These energies may be taken as representative for the experiments which we are considering. The primary ionizations have been spaced at an average distance apart, instead of at random. The secondary ionizations are shown vertically above the primaries, on approximately the same distance scale as the primaries. The electron ionization secondaries have been distributed according to the data of Table II, and the proton secondaries in somewhat the same manner. In Fig. 6 the ionization is supposed to occur in tissue which is taken to be $760\times800=6.08\times10^5$ times as dense as air at 1 mm p.

There is much evidence to show that the changing or killing of a cell is due to the interaction of electrons with sensitive volumes of about the size of genes (excitation or ionization).

Table I. *Comparison of film density from mercury pool tube and from Coolidge tube.*

Film	Density		Ratio
	Mercury	Coolidge	
1a	1.97	1.91	1.03
1b	2.11	2.03	1.04
2a	2.03	1.81	1.12
2b	2.03	1.86	1.09

Table II. *Distribution of ionization by 25 kv electron.*

No. of ion pairs in clump	Percentage of total number of clumps
1	47
2	22
3	12
4	7
>4	12

[2] For example: J. H. Lawrence, P. C. Aebersold, and E. O. Lawrence, Proc. Nat. Acad. **22**, 543 (1936). Zirkle and Aebersold, Am. J. Cancer **29**, 556 (1937).

[3] Data from von Engel and Steenbeck, Elektrische Gasentladungen **1**, 34, 35, 51 (1932).

[4] C. T. R. Wilson, Proc. Roy. Soc. **104**, 192 (1923).

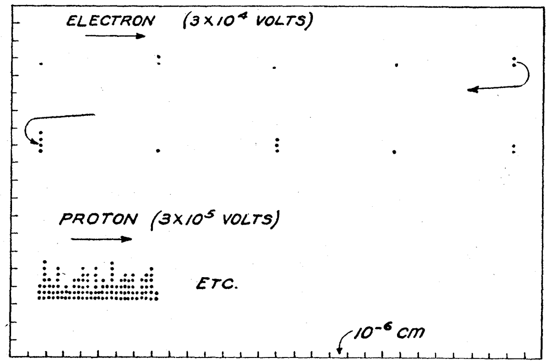

FIG. 6. Distribution of ionization along the paths of an electron and a proton in body tissue.

The dimensions of a gene are supposed to be of the order of magnitude 5×10^{-7} cm.

If the interaction consists in the production of a single ion pair in the sensitive volume one would expect no appreciable difference in efficiency between electron ionization and proton ionization for the same total dose (total ionization). By fai the greater part of the ionization is wasted, as it occurs in tissue outside the sensitive volumes, so that it would make no appreciable difference if a proton wasted a few more ions by making several in a sensitive volume where only one was needed.

On the other hand, if the interaction requires the simultaneous production of two ion pairs in the gene, the protons should be about twice as efficient as the electrons, because it is evident from Fig. 6 that in only about 50 percent of the electron ionizations can two ions be produced within a single sensitive volume of dimensions 5×10^{-7} cm. This difference in efficiency is of the order of that reported for the neutron experiments. These considerations, of course, do not exclude the possibility that there may be an error in using an ordinary dosimeter to estimate the ionization produced by neutrons in a biological specimen.

In the work with the mercury pool x-ray tube most of the biological experiments were done with "shots" of 3.5 roentgens delivered in about 5×10^{-6} sec. If the ions resulting from each shot are considered to be made simultaneously, it is of interest to see whether their concentration is sufficient to expect different biological effects on the basis of Fig. 6. Assuming tissues to be 800 times as dense as air at atmospheric pressure, the number of ions produced in 1 cc of tissue for a dose of 3.5 r is $(800\times3.5)/(4.77\times10^{-10})=5.9\times10^{12}$. Hence the average distance between these ions is 5.5×10^{-5} cm. Thus the spacing between tracks of individual high speed electrons is large compared with the spacing of ions along one single track, and on the basis of Fig. 6 these x-rays should behave biologically like x-rays of ordinary intensity.