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OIL-IMMERSED X-RAY GENERATING OUTFITS*

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I. INTRODUCTION.

THE medical application of the *x*-rays has almost invariably been attended by the possibility of accidental electric shock to either the patient or the operator. In the early history of the art, contact with the high tension circuit involved only annoyance and discomfort; but with the advent of high-power installations, that which had been merely a possible source of annoyance became a real danger.

This danger could, at any time, have been eliminated by putting the entire high tension system, including the tube, into an earthed metallic enclosure. This method, however, when applied to earlier forms of *x*-ray apparatus, would in general have rendered them bulky and, mechanically, relatively inflexible.

With the advent of a self-rectifying *x*-ray tube, which is stable and can be made very small, it became interesting to mount the *x*-ray tube inside of the transformer tank and in the same oil with the transformer. The following consists of a description of a small experimental model of such an outfit, together with a discussion of some of the possible modifications and a summary of the inherent advantages and limitations of the method.

II. DESCRIPTION OF A SMALL EXPERIMENTAL MODEL.

1. *General Description.*—A complete oil-immersed outfit is shown in Fig. 1. The rectangular metal box, adjustably mounted on the tube stand, contains the *x*-ray transformer and, below this, the special *x*-ray tube. A low tension cable is seen leading from this, the generating outfit, to the control box at the right of the picture. A second cable, attached to the other end of the control box, leads to the supply mains.

A side view of the generating outfit in partial cross section is shown in Fig. 3. (In this case the cone has been removed and the outfit has been rotated through an angle of 180° from the position shown in Fig. 1, so that the *x*-ray tube is now above instead of below the transformer.) Fig. 4 shows a partial sectional end view. In Fig. 3, 1 and 2 are the high tension coils of the transformer. The tube is mounted directly over these. It is made of thick lead glass with a small lime-glass window which is set to face a thin re-entrant window in the bakelite cover, 3, of the tank. The *x*-rays which emerge from the tank have to pass through these two windows and a thin intervening layer of oil.

To permit of operation in all positions, two oil-expansion chambers, 4 and 5, in Fig.

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4, are provided at the bottom, and the balance of the tank is completely filled with oil. (One of the oil-expansion chambers, 5, is also seen in Fig. 3.)

The tank is of metal, and the cover, 3, is of bakelite. A thin layer of aluminum may be mounted on top of this and metallically connected to the tank. If then the tank is connected to earth, the whole high tension system is inside of an earthed metal enclosure from which nothing but *x*-rays can emerge. The high-tension danger is then seen to be completely eliminated.

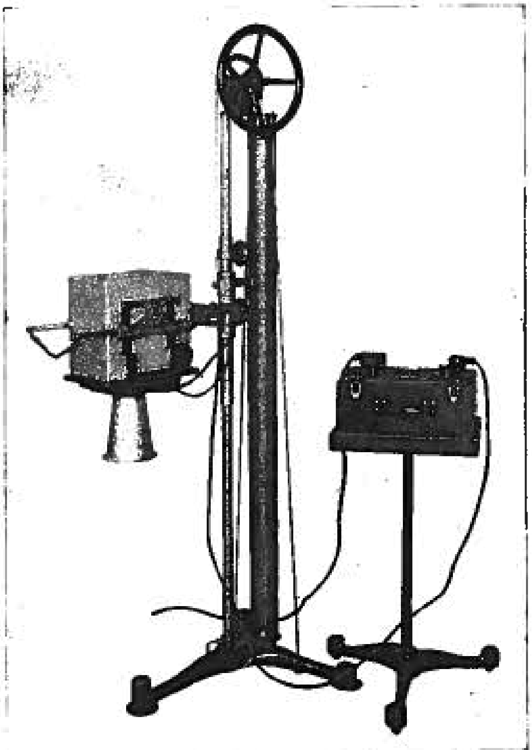

FIG. 1.

The generating outfit, as shown in Fig. 3, is suitable for 10 milliamperes at 60000 volts (useful), and weighs 54 pounds. Light weight is of course desirable to promote ease in handling. Furthermore, the weight of the generating outfit determines the weight and bulk of the supporting stand.

2. *The Transformer.*—The transformer is made as small as is consistent with the satisfactory operation of a tube rectifying its own current and carrying the above mentioned load.

3. *The Tube.*—As the bulk of the metal tank which is to contain the transformer and tube is partly dependent on the size of the latter, it becomes desirable that the tube shall be small. There is also another reason for this, for the smaller the bulb and the shorter the anode arm, the shorter will be the heat path from the focal spot to the outside cooling medium, and, hence, the more effective will be the cooling of the anode.

As has been pointed out elsewhere,[1] the size of bulb may be reduced by the use of thick glass. This brings with it the same improvement in operation in oil as it does in air.

For operation in oil, the side arms of the tube may be made very short. (For use in the air they have to be relatively long to prevent arc-over between terminals and to prevent leakage over the surface of the glass, especially in damp weather.)

Fig. 2 shows a full size cross-sectional drawing of the tube, which operates well in oil at 60000 volts (useful). Both 5 and 10 milliampere models have been built, and the same design with the same dimensions, but with larger focal spots, should be equally well suited to tubes of higher current-carrying capacity. Except for a small transparent window of lime glass, this tube is made throughout of glass containing 55 per cent by weight of the element lead.[2] This glass offers the same protection as sheet lead of one-fourth its thickness. The wall-thickness of the bulb is ¼ inch, hence the protection offered is equal to that of 1/16 inch of sheet lead.

As the outer end of the copper anode rod is in direct contact with the oil, no radiator is required.

[1] W. D. Coolidge, AMERICAN JOURNAL OF ROENTGENOLOGY for July, 1919, pp. 8-10.

[2] With the oil immersed type of outfit, *x*-ray protection could readily be obtained by lining the tank with sheet lead, but weight and bulk are saved by securing protection through the use of the high lead-content glass for the tube.

4. *Air Tanks to Permit of Operation in Any Position.*—The location of the tube in the same oil with the transformer results in a greatly increased heating of the oil, and, hence, in a greatly intensified oil-expansion problem. Of, say, 1000 watts of electrical energy delivered to the primary of the transformer, all but about 0.03 watts (the energy in the useful *x*-ray beam which comes out through the tube-window) will be finally delivered to the oil in the form of heat energy.

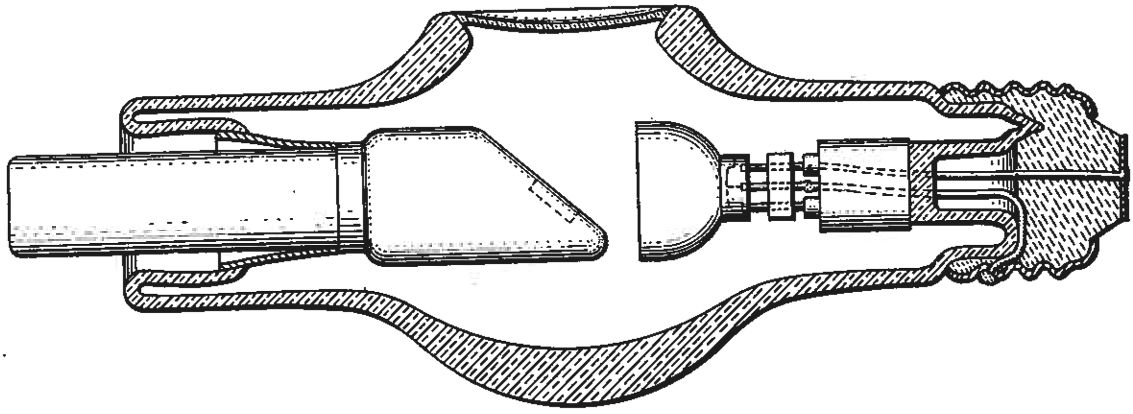

Fig. 2.

The tank and other metal parts involved, expand relatively little, but the oil expands strongly on heating. As a result, with the outfit in question, there is an oil expansion of 10 cubic centimeters for each degree C. of temperature rise.

A natural way of taking care of this would be to leave an air space in the top of the transformer case, and then, as the oil expands, it would compress the air in this space. But to save weight and bulk, the tank is made as small as is safely consistent with the required high tension insulation. Such a transformer could be operated when right side up, but in certain other positions it would be found that there was air where there should be oil, and that the transformer, if operated, would break down.

The field of usefulness of the device is greatly extended by making it possible to operate it in any and all positions. This result is attained by the use of the air chambers, 4 and 5, in Figs. 3 and 4. These air chambers are made of thin sheet metal and connect in each instance with the main tank by means of a metal capillary tube (6 and 7) leading to the center of the chamber. Such an amount of oil is originally put into each of these tanks that, even at the lowest temperature to which the device will ever be subjected, the inner end of the capillary will always be below the level of the oil in the chamber. The balance of the chamber is filled with air at atmospheric pressure. The main tank is filled full of oil so that the only air in the device is that in the special air chambers.

Figs. 5 and 6 show the position of the oil level with respect to the inner end of the

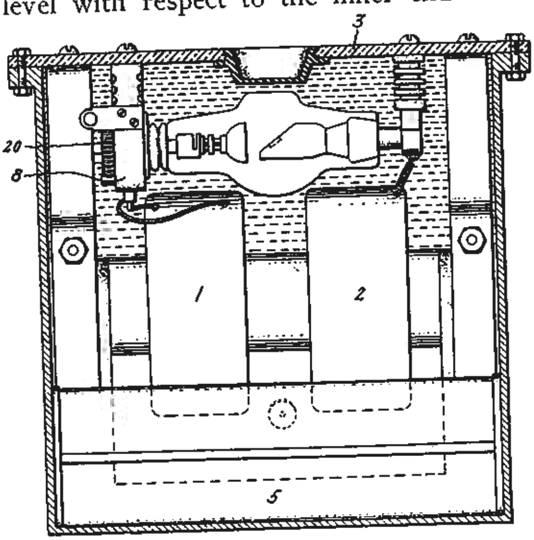

Fig. 3.

capillary tube, with two other positions of the air chamber 4. In no position of the chamber can the air escape into the main tank.

5. *Allowable Temperature Range of Operation.*—With the design in question, the total amount of oil involved is 11200 c.c. The total volume of air at atmospheric pres-

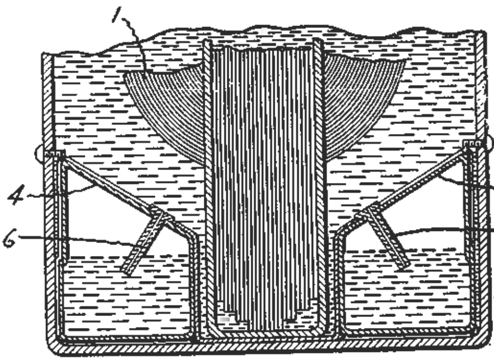

FIG. 4.

sure in the tanks is 710 c.c. If the oil is allowed to expand until this volume of air is reduced to ¾ of this amount, the pressure on the inside of the tank will be 4/3 of what it was and will amount to 5 pounds per square inch above the atmosphere (neglecting the effect of temperature acting directly on the gas pressure). This is a reasonable pressure for the transformer tank in question and allows an oil expansion of 177 c.c. As the oil expansion is 10 c.c. per degree C., an expansion of 177 c.c. will correspond to a temperature rise in the oil of 17.7°C. above the 20° at which the case was filled.

As has been said, the air tanks were originally filled more than half full of oil; enough so, in fact, to allow the oil temperature to drop to 0°C. before air can escape from the air tanks. The outfit as it stands then can be conservatively operated with an oil temperature ranging from say 10° to 38°C.

This allowable temperature range can, of course, be extended by the use of larger air tanks.

6. *Allowable Time of Continuous Full-Load Operation.*—Assuming 18°C. as the allowable temperature rise above that of the room, it is interesting to calculate how long the outfit can be continuously operated with 10 milliamperes at 60,000 volts.

The electrical efficiency of the transformer has not been measured, but for this rough calculation it may be assumed that 80 per cent of the energy put into the primary is delivered as high tension electrical energy to the tube. In this case there is an input into the transformer of $\frac{600}{.80} = 750$ joules per second $= \frac{750}{4.2} = 180$ calories per second.

The heat capacity of the system is 6000 calories per degree centigrade.

To raise the temperature 18°C., will call for operation for $\frac{6000}{180} \times 18 = 600$ seconds $= 10$ minutes. This time could be extended by the use of larger air tanks, which would permit of a greater allowable temperature range.

7. *Wiring Diagram of Generating Outfit.*—A schematic wiring diagram is shown in Fig. 7, in which 21 is the low tension coil of the transformer and 1 and 2 are the high tension coils. Coil 23 consists of but a few turns of relatively coarse wire. It is electrically connected to the high tension coil 1, and serves as a source of heating current for the filament of the *x*-ray tube. The filament

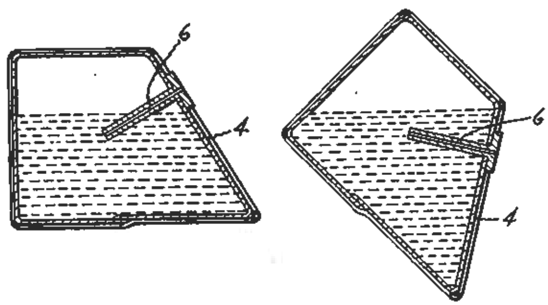

FIG. 5. FIG. 6.

current is controlled by a little rheostat 8. Wires lead from the inner ends of the high tension coils out through the metal tank, indicated in the figure by the dotted rectangle, to 24, a milliamperemeter located in the control box. At the bottom of the figure, a connection is shown running from the metal tank to ground.

8. *Mechanical Means for Adjusting Rheostat in Filament Circuit.*—Fig. 9 is a sectional end view of the upper portion of the generating outfit. (For the sake of clearness, it is drawn to a larger scale than the corresponding side and end views, Figs. 3 and 4.) It shows a mechanical means for adjusting the rheostat, 8, in the filament circuit, from outside the tank. (See also Fig. 8, which is a length section of the rheostat.) The little rheostat consists of a spiral of resistance wire, 20, which is mounted on a circular insulating support, which also carries the receptacle into which the cathode base of the tube screws. The rheostat contact arm, 10, and the two ratchet wheels, 11 and 19, are rigidly connected together and rotatably mounted on a horizontal shaft. The teeth of the two ratchet wheels point in opposite directions. The metal fingers 12 and 13 are made of flat spring material and are carried by the bakelite push-rods 9 and 18. Each of these fingers engages with one of the ratchet wheels. If one of the push-rods, 9, for example, is alternately pushed and released, it produces a clock-wise rotation of the rheostat contact-arm 10. A similar use of the other push-rod results in counter-clock-wise rotation of 10. The push-rods are operated by means of the push-buttons 14 and 15, each of which is attached to a flexible diaphragm in the side wall of the metal container. For greater flexibility, pieces of Sylphon tubing, 16 and 17, are used in place of flat diaphragms. The inner surface of each flexible diaphragm rests against the end of one of the push-rods.

One push-button then serves to increase the filament current and, hence, the milliamperage flowing through the tube, while the other serves to lower it.

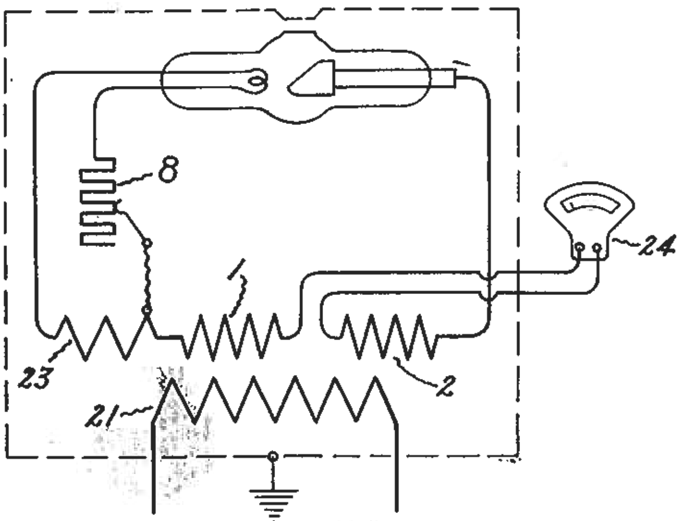

Fig. 7.

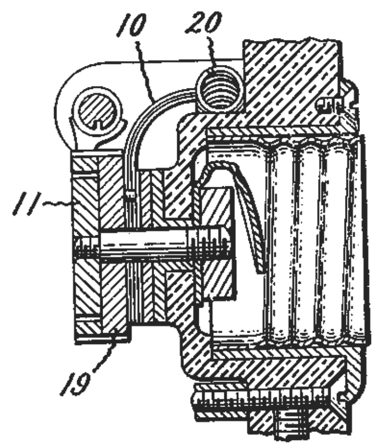

Fig. 8.

9. *The Control Box.*—This is, with a few changes, like one which has already been described in a paper on apparatus for portable work.[3] It is shown in Fig. 10 and contains an auto-transformer with a multiplicity of taps and corresponding special switch. By means of this combination it is possible to vary the voltage supplied to the *x*-ray transformer by steps of 2 volts through a range of 32 volts.

The voltage delivered by the auto-transformer to the *x*-ray transformer is indicated by a voltmeter, and the corresponding high tension voltage is known from a sphere-gap calibration made before the transformer was put into the tank.

Current passing through the tube is shown by a milliammeter, which is connected in to

[3] l.c. pp. 13-16.

the middle point of the high tension secondary. There is also a circuit-breaker, time-switch, pilot lamp and push-button *x*-ray switch.

10. *Method of Operation.*—If the voltage is to be kept constant, at 60,000, for example, the operation is very simple. With this particular outfit, a sphere-gap calibration has shown that for 60,000 volts and 5 milliamperes, a primary voltage of 105 is required. The resistance in the filament circuit is then adjusted so that the tube carries

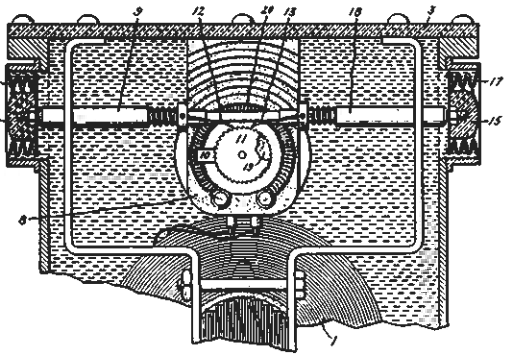

Fig. 9.

5 milliamperes when the primary voltage is 105. It should then be unnecessary again to touch this adjustment of the rheostat in the filament circuit. The milliamperage can be subsequently controlled by the auto-transformer switch, and as the following data will show, this can be done without appreciably affecting the high tension voltage. This is due to the fact that the filament current is determined by the primary voltage and that the electron emission goes up so very rapidly with the filament current.

Primary Volts	*Milliamperes*
101	4.2
104	6.0
106	8.7

In the above table, the primary voltage has been increased by 5 per cent, and this has caused an increase of 107 per cent in milliamperage. A sphere-gap calibration of the transformer shows that the corresponding secondary voltage increase was only 3 per cent. In other words, the above method of regulation made it possible to increase the milliamperage 107 per cent while the secondary voltage increased only 3 per cent.

This method of operation has a great deal to recommend it, especially in radiographic work. If the line voltage is constant, there is nothing to do in making the exposure but to set the time switch and press the button. When the line voltage is very variable, one has merely to see that the voltmeter reading is right before closing the switch, and then, if necessary, operate the auto-transformer switch during the exposure to hold the milliamperage constant.

III. AIR COOLING OF AN OUTFIT FOR CONTINUOUS OPERATION.

For continuous operation or for any sufficiently severe service, the cooling of the oil could be facilitated by the use of a fan or blower and cooling vanes on the outside of the tank. In this case it would also help to make the tank of some good heat-conducting metal, such as copper.

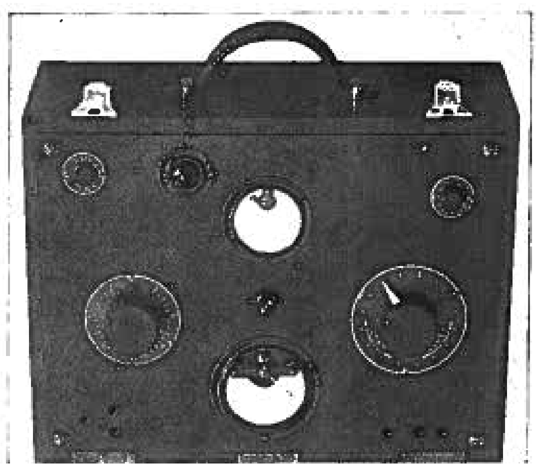

Fig. 10.

IV. WATER COOLING FOR THERAPEUTIC OR OTHER HEAVY DUTY WORK.

Cooling coils of copper tubing could be placed inside of the oil and at a safe distance from the high tension system, or such cooling coils could be soldered to the outside of the tank. In either case, tap water could then be safely passed through the cooling coils. It will be seen that this is entirely different from the ordinary water-cooling of an *x*-ray tube, for it does not in any possible way endanger the patient. Nor does it necessitate insulating the cooling water. Furthermore, owing to the absence of corona, rubber tubing can be satisfactorily employed as a flexible means of getting water to and from the copper cooling coils. (Rubber disintegrates very rapidly in the neighborhood of high tension discharges.)

V. DIRECT WATER-COOLING OF THE ANODE.

This is also possible with the oil-immersed system, for the tubular anode rod can be soldered in to a metal plate, and this plate can, in turn, be fastened with a gasket into a hole in the wall of the tank. In this case it becomes desirable to connect the inner end of the high-tension winding directly to the metal tank and thence to earth.[4]

Fig. 11 shows a sectional view of a 40 milliampere, 60,000 volt model of this type which has been built. The schematic diagram of connections is shown in Fig. 12. In the light of the other diagrams, these figures are almost self-explanatory.

The cathode end of the *x*-ray tube is attached to a socket containing a little rheostat, which is flexibly mounted on the single high-tension coil of the transformer. The inner end of this high tension coil is connected through a milliammeter to the metal tank and thence to earth. The anode end of the tube is also electrically connected to the metal tank. The anode is cooled by tap water entering at *a* and leaving at *b*.

As the transformer is so small, and as this model was intended for continuous full-load operation, a water-cooling coil, *c*, is shown soldered to the outside of the metal container.

A window of bakelite or aluminum or some other material transparent to *x*-rays is mounted in the wall of the metal tank opposite the transparent window in the *x*-ray tube.

VI. FILAMENT HEATING FROM AN EXTERNAL SOURCE.

For certain applications, the cathode end of the tube may advantageously be connected to the metal tank and to earth. Such an arrangement is shown diagrammatically in Fig. 13. The transformer is here seen to have only one high tension terminal. The

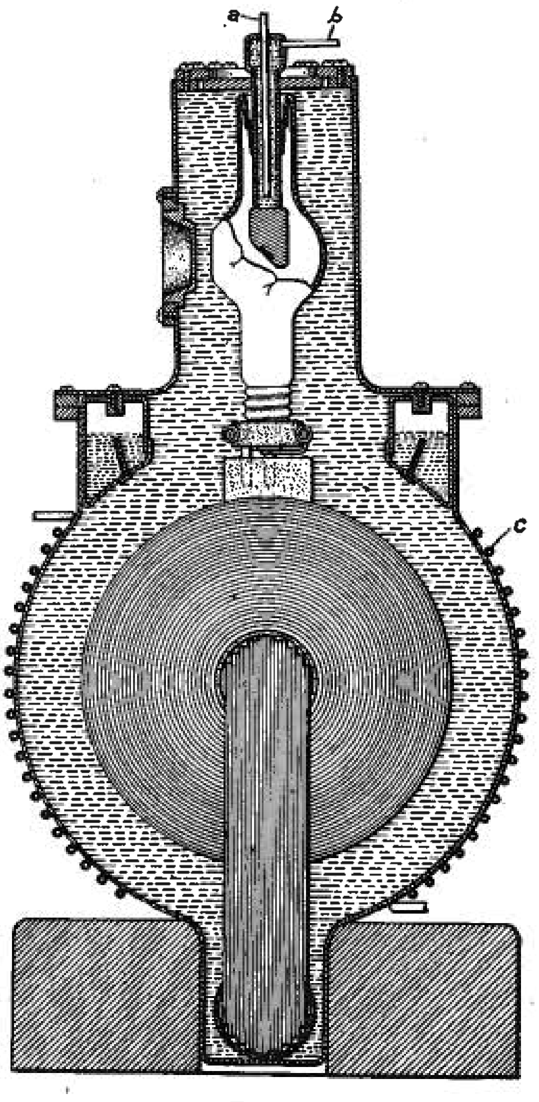

FIG. 11.

[4] For very high voltage work in air such a system is objectionable, for it results in increased corona trouble. This objection does not hold, however, in the oil-immersed outfit.

above system makes it possible to have the filament lighted before closing the x-ray switch (thus doing away with the time-lag which is otherwise present), and brings the control of filament temperature outside of the oil and, if desired, makes it entirely independent of the high tension voltage. This is, of course, conducive to extreme flexibility of operation.

eral fluoroscopy is perhaps sufficiently obvious. It will be seen that when used under the table it greatly extends the allowable tube travel.

For fluoroscopic control in the reduction of fractures or any other surgical work, the oil-immersed type of outfit seems especially indicated, for it eliminates the electrical danger to the surgeon and his assistants, as

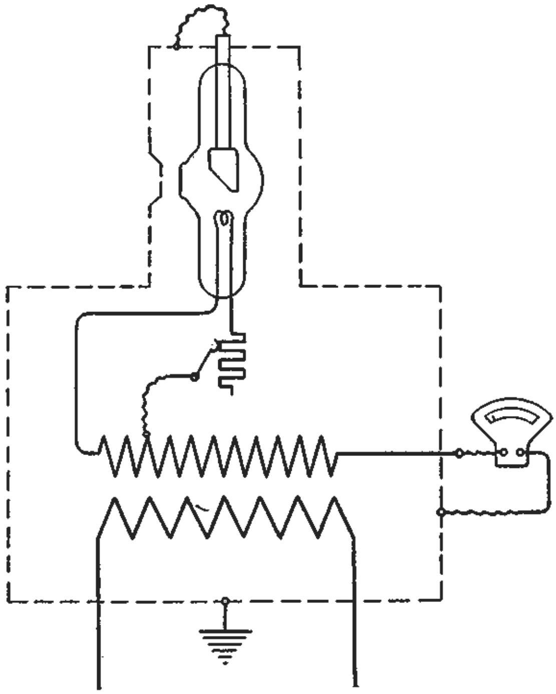

FIG. 12.

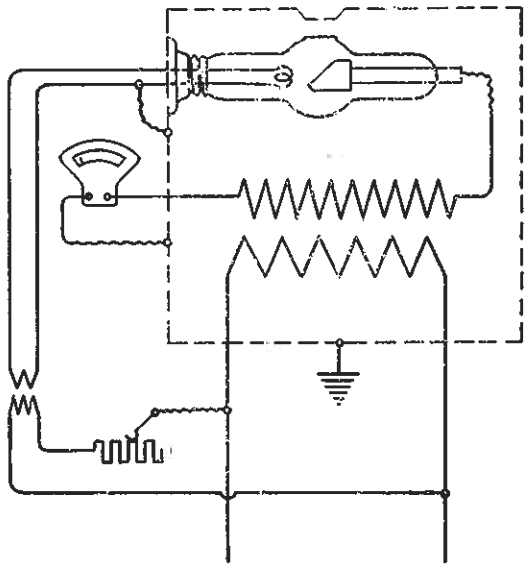

FIG. 13.

well as doing away with the fire hazard attendant upon the use of high tension electricity in the presence of ether vapor. It can furthermore be used under the surgeon's operating table without the need of any precautions to keep blood and water off of it.

In therapy the oil-immersed type of outfit seems to offer special advantages. Aside from the general advantages, which will be summed up in the next section, it should help in work under the arm and in the treatment of body cavities. For the x-ray tube could be placed in a small cylindrical side arm leading off from the main transformer tank, as in Fig. 11 for example. This metal side-arm is connected to earth and could be

VII. POSSIBLE APPLICATIONS OF THE OIL-IMMERSED TYPE OF OUTFIT.

For radiographic work it seems thoroughly feasible to use such an outfit as that shown in Fig. 1. Higher power outfits of this same type should be equally satisfactory. One for 50 milliamperes and 60000 volts has been built. It is simply a larger edition of the one shown in Fig. 1 and weighs 75 pounds. In the field of radiography it is, perhaps, more especially in connection with high power work that the elimination of the high-tension risk will be most appreciated.

The application of such an outfit to genwater-cooled. It could then safely be brought into contact with the patient. In this way, it would be possible to bring the focal spot of the tube to within a very short distance of the skin.

In experimental therapy, the system should make it possible to use, in a room of ordinary size, the highest voltage for which an *x*-ray tube can be developed.

VIII. ADVANTAGES OF THE OIL-IMMERSED SYSTEM.

The main advantages derivable from such a system are the following:

(a) Eliminates all danger of electric shock to patient or operator.

(b) Eliminates all corona discharges with attendant noise and odor.

(c) Eliminates fire-risk in presence of ether vapor.

(d) Makes it easy to get any desired amount of *x*-ray protection, for, if necessary, the tank itself can be lined with metallic lead.

(e) Makes practicable, even in small rooms, the use of as high a voltage as that for which an *x*-ray tube can be developed.

(f) Disposes of all light emitted by tube, which is a convenience in fluoroscopy.

(g) Makes it possible to bring the focal spot much nearer to the patient than is ordinarily practicable. This might be useful in certain therapeutic applications.

(h) Makes tube mechanically stronger by permitting use of shorter arms and a shorter anode rod.

(i) Gives greater heat conduction from focal spot to outer end of anode rod, by shortening the distance the heat has to travel.

(j) Assists in removal of heat from outer end of anode rod, as oil is a more effective cooling medium than air.

(k) Permits of safe and convenient use of tap water for cooling of oil or anode.

(l) Reduces danger of tube breakage by putting tube in a good damping medium (oil) and inside of a metal container. It furthermore eliminates all handling of the tube.

(m) Eliminates effect of humidity on performance of apparatus, a matter of considerable importance in moist climates. It also prevents the deposition on the tube of a conducting layer of salt spray at the seashore.

IX. A LIMITATION OF THE METHOD.

With such an outfit it is still necessary, in diagnostic work, that the focal spot of the tube shall be held stationary in space. As the weight of the tube and transformer is obviously much greater than that of the tube alone, the method necessitates a much more rigid, and hence larger and heavier, tube stand than would be required to support the tube alone.

In closing, the author wishes to acknowledge the assistance of Mr. L. E. Dempster and Mr. W. K. Kearsley, both of whom have actively contributed to the development work described in this paper.

DISCUSSION

DR. BYRON C. DARLING.—I would like to ask Dr. Coolidge about the volatilization of tungsten in his tube. The smaller you get your tube, the smaller the total area of your circumference, and I am not enough of a mathematician to figure out the proportional area between a 6 inch bulb and a 7 inch bulb and a 1½ inch bulb, but it runs somewhere between 1 and 5. That would make your smaller tube last a much shorter time, which would make our bill five times what it is now for the same exposure time. It seems to me that the work that is being done to refine the apparatus is work well taken and time well spent. It occurs to me that a combination of the transformer and rotary switch and oil as one unit, and a tube in oil as another unit with Dr. Johnston's safety device, and some overhead high tension system that is safe, may be the ultimate solution for a man who is doing nothing but *x*-ray work in his office. The portable outfit, of course, is another matter. I have wondered why Dr. Coolidge did not put a radiator on his 7 inch bulb, all tungsten target tube, also the regular size copper and tungsten anode. It would seem to me that if it is an advantage to get rid of heat it might be used in every size. The small button on the tungsten and copper target self-rectifying tube favors the heating of the copper surrounding, and if over-heated, the whole button falls out. The button is too small now.

Another question I would like to ask is how large a milliamperage capacity can be built with the suppressed wave type of apparatus mentioned.

Dr. W. D. Coolidge.—The size of an *x*-ray tube should, I think, be kept as small as is consistent with satisfactory operation, and for the following reasons:

(1) A small tube lends itself to more complete *x*-ray protection.

(2) For a given amount of protection, the small tube with its protecting envelope will weigh less and can therefore be used with smaller, lighter, and more convenient accessories.

(3) It is less liable to breakage in handling.

With conservative operation, there is no appreciable blackening of the bulb of even the smallest *x*-ray tubes.

It is quite feasible to have the *x*-ray tube in a separate tank of oil instead of putting it into the same tank with the transformer. The latter system has several advantages, however, which are not possessed by the former. For example, it puts the entire high tension circuit inside of a grounded metal inclosure.

As to the question of how large a capacity you can have in a system where the tube rectifies its own current: I am very sure that there is no limit. We have operated self-rectifying water-cooled tubes continuously for hours at a time, with as much as 5 and even 10 kilowatts of energy, and there appears to be nothing but the size of the focal spot and the size of the anode to set a limit to the allowable energy input.

Dr. Byron. C. Darling.—Transformer 100 kilowatts?

Dr. W. D. Coolidge.—Yes indeed. There is no trouble at all. It simply means a suitable design and the use of plenty of iron and copper.