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1000 CURIE COBALT UNITS FOR RADIATION THERAPY

I. THE SASKATCHEWAN COBALT 60 UNIT

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Introduction

In August 1951 a 1000–curie cobalt unit was installed in the University Hospital at Saskatoon. The unit was built by the Acme Machine and Electric Co., Saskatoon, for the Saskatchewan Cancer Commission. The radioactive cobalt was produced in the nuclear reactor at Chalk River, Ontario. The activation of the cobalt, the loading of the unit, and the design of the treatment head will be described in this paper. A photograph of the unit as installed is reproduced in Fig. 1.

Fig. 1.
Photograph of the unit.

Design of the head

Diagrams of the treatment head are shown in Figs. 2 and 3. The head, weighing over a ton, consists of a steel-encased lead cylinder with rounded ends, 20 in. in diameter and 22 in. high. On one end of the head a steel plate E, to be used for mounting accessories, is welded to the steel container. A tapered hole is cut through this plate and through the lead to end at a point 5 in. from the lower face. A removable cylindrical lead plug S, 9 in. long, encased in steel, fits into the head from the opposite end. Situated near the centre of the head is a steel-encased lead wheel which appears in Figs. 2 and 3. Two cylindrical pieces of heavy metal* 2 in. in diameter and $\frac{1}{2}$ in. thick (L_1 and L_2 of Fig. 3) were silver soldered to a rectangular bar of heavy metal $7 \times 1{\cdot}5 \times 1{\cdot}5$ in. The axis of this bar of heavy metal was along a diameter of the wheel. The rest of the surface of the wheel was made of steel, and the interior was filled with lead. After this composite wheel had been fabricated, a tapered hole was bored along the axis of the heavy-metal bar to take the unit shown in Fig. 7. The wheel is mounted on a shaft carried by bearings inside the steel container as shown in Fig. 3. If at any time trouble should develop in the wheel mechanism the source would be returned to the lead safe and the whole unit, shown in Fig. 3, removed from the head.

The wheel is rotated by a small two-phase motor through a friction clutch. Manual rotation of the wheel is possible with the handle. The machine is shown in the "on" position in Figs. 2 and 3. To turn the machine "off", the motor shown in Fig. 3 is energised, and the wheel is rotated through 180°. This introduces into the path of the radiation 6 in. of "heavy metal" which is equivalent to about 9 in. of lead.

Considerable care was exercised in the design of the unit to prevent radiation leaks along the cracks between moving surfaces. When the cobalt is in the "on" position radiation leaks through cracks are negligible in comparison with the scattered radiation present in the room. In the "off" position, several possible radiation leaks had to be considered in the design. A clearance of $\frac{1}{32}$ in. between the moving wheel and the stationary steel plate was necessary to ensure that the wheel would not bind. No radiation can escape directly along this line, but some could certainly be scattered down it. The lugs L_1 and L_2 of heavy metal introduce into this path two right-angle bends. After two Compton scattering

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* "Heavy metal" is an alloy containing tungsten, nickel and copper, with a density of about 17 gm./cm^3.

processes at right angles the radiation is soft and readily absorbed. For the same reason the steel-encased lead plug S (Fig. 2), which fits into the top of the head, was provided with a larger section which cuts down radiation leaks along the line R. Radiation leaks along the line P (Fig. 3) were reduced by the two right-angle bends at P and Q. Even with these precautions a crescent-shaped piece of lead (not shown in Fig. 3), 2 in. thick, had to be added at X_7 to reduce radiation leaks along the line P. Dosage levels outside the head will be discussed later.

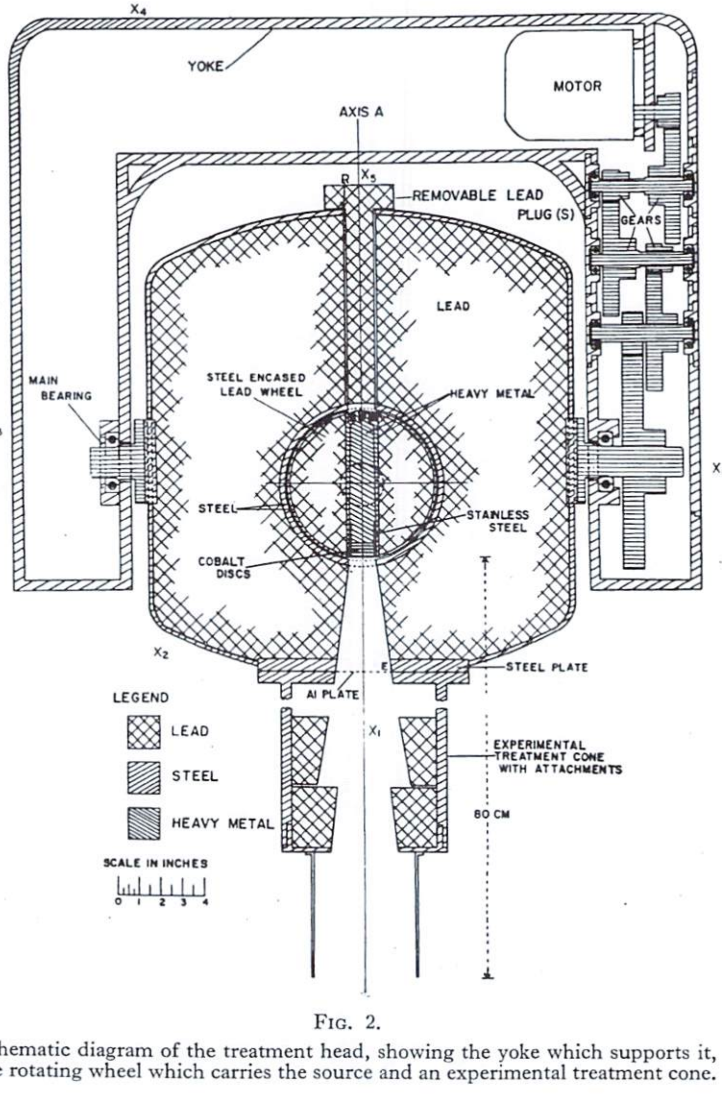

FIG. 2.

Schematic diagram of the treatment head, showing the yoke which supports it, the rotating wheel which carries the source and an experimental treatment cone.

The treatment room and mounting of head

An elevation view showing the method of support of the treatment head is shown in Fig. 4. Rotation (R) of the head is achieved by means of the motor and gears shown in Fig. 2, and is limited to the angle indicated. This means that the radiation is directed either downward or against the outer wall of the hospital. The unit can be raised or lowered by a motor connected to the lifting drum D. Most of the weight of the head is balanced by the counter weight. The unit has a vertical motion of 5 ft. The unit is prevented from rotating about a vertical axis by keyways in the sleeves S_1, S_2 and S_3. The sleeve S_3 is fastened to the four-wheeled carriage which can move along the overhead track a distance of 7 ft. The horizontal motion H is produced by a motor geared to one of the wheels. The motors are all energised through relays which are controlled from a small push-button control panel suspended from the carriage.

A plan view of the room is shown in Fig. 5. The concrete walls of the room are 12 in. thick. The basement room below the treatment room is used for storage and is supplied with interlocking switches which shut off the unit when the door in the room below is opened. The doors to the treatment room are faced with $\frac{1}{8}$ in. of lead and are also supplied with interlocking switches. The concrete shield at the doorway is necessary to reduce radiation outside the doors to the permissible level. This shield is 7 ft. high. The observation window is filled with eight layers of 1 in. plate glass. A steel turntable mounted beneath the unit will be used in rotational therapy. The top of the table is flush with the floor, and its rate of rotation can be varied from 0·06 to 0·36 r.p.m.

Control panel

The control panel contains a timer, a speed control for the turntable, an electrical tachometer giving the rate of rotation of the table, and a key-operated switch. When the machine is turned to the "on" position by the key-operated switch, the motor (Fig. 3) rotates the wheel through 180° against a stop which locates the wheel in exactly the right position. A microswitch on the stop shuts off the power to the motor and starts the timer. The friction clutch allows the motor, because of its inertia, to rotate a little further than the wheel after the power has been shut off. At the end of the treatment time, the motor rotates in the opposite direction and the cobalt is returned to the "off" position. It requires 5 seconds for the cobalt to move from one position to the other. The unit is shut off if any of the interlocking doors are opened during treatment. Green

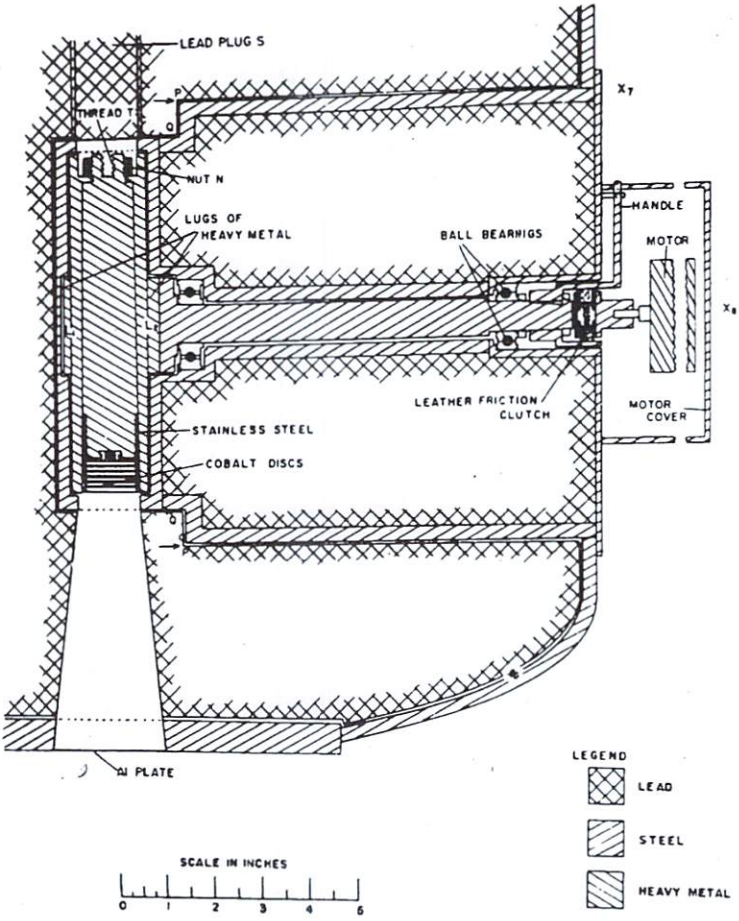

Fig. 3.

Diagram of the lead-filled steel container which holds the bearings for the rotating wheel. The diagram shows how this unit fits into the head shown in Fig. 2.

and red lights on the control panel over the doors and on the unit itself indicate the position of the wheel carrying the cobalt.

Activation of cobalt

Twenty-five cobalt discs, 0·0521 cm. thick, 2·55 cm. in diameter, each having a mass of 2·31 gm., were irradiated in the Chalk River pile. For irradiation in the pile the discs were held in two layers between two flat aluminium plates, and were arranged in the available space so that overlapping was kept to a minimum. The holder was designed in such a way that 66 per cent. of the total area of the discs was unshielded and 34 per cent. of the total area was two discs thick.

An estimate of the neutron shielding by the cobalt itself has been made with the help of W. R. Dixon (1951). By considering that the cobalt is in the form of an infinite plane layer of thickness t, and that it is situated in an isotropic distribution of thermal neutrons, it can be shown that the efficiency (E) of irradiation is given by:

$$E = \frac{1}{2\mu t}\left\{1 - 2\int_{1}^{\infty}\frac{e^{-\mu t y}}{y^{3}}\,dy\right\} \ldots\ldots\ldots (1)$$

The efficiency, E, is defined as the total activity achieved in a sample, of thickness t, expressed as a percentage of the activity which would have been achieved had there been no shielding. In this expression μ, the linear coefficient, is equal to $N_o\sigma$ where N_o is the number of atoms per cm^3 and σ is the cross section for thermal neutrons. σ has been taken as 34·2 barns (Yaffe, Hawkins, Merritt and Craven, 1951). Expression (1) has been evaluated for different values of t and is plotted in Fig. 6. It is seen that for cobalt 0·052 cm. thick the efficiency of irradiation is 78 per cent. For a sample 0·104 cm. thick this efficiency is 65 per cent. For the 25 discs used in this source the average efficiency is 0·66 (78) + 0·34 (65) = 74 per cent. A detailed discussion of neutron shielding will be published elsewhere.

From a knowledge of the neutron flux in the pile at the position of the cobalt and the time of irradiation, the specific activity expected is 38·1 curies per gm. if the efficiency of irradiation is 100 per cent. Correcting for the efficiency of irradiation, one obtains 28·2 curies per gm. as of June 6, 1951, when the cobalt came out of the pile. The total source of 25 discs should have an activity of 1630 curies. Measurements of the activity of the source were made three months after it came out of the pile. During this time the source will have decayed at the rate of 1·1 per cent. per month to 1580 curies.

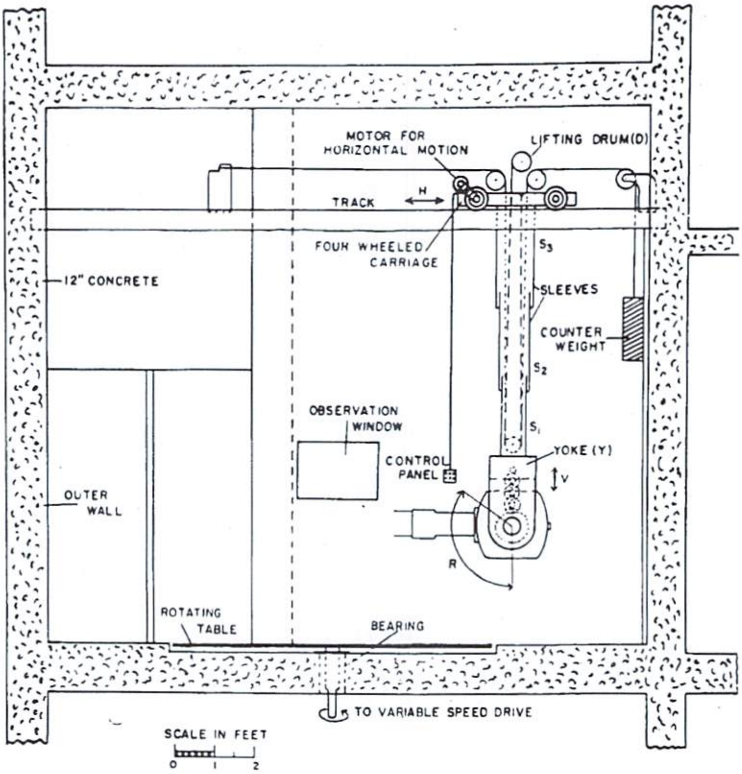

FIG. 4.

Schematic elevation of the treatment room, showing the unit and the motions of which it is capable.

Loading and Shipping of Cobalt

The cobalt discs were transferred from the pile to the stainless-steel cup, shown in Fig. 7. This cup has a $\frac{1}{32}$ in. bottom face and is threaded to take a cylindrical piece of heavy metal. The transfer process was carried out at Chalk River by remote control using equipment especially designed there for this purpose. After the discs were placed in the stainless steel cup the heavy-metal cylinder was screwed tightly into place, to prevent the escape of cobalt oxide dust.

The unit shown in Fig. 7 was shipped to Saskatoon in a cylindrical lead safe, 22 in. high and 22 in. in diameter. The dosage-rate at the surface of the safe was 7 mr. per hour.

In all subsequent manipulations of the cobalt source, the unit shown in Fig. 7 was handled as one piece.

Loading the head

To transfer the cobalt from the lead safe to the treatment head, the treatment cone attachments shown in Fig. 2 were removed, the wheel was rotated to the "on" position and the lead plug S removed. In this way a clear hole exists right through the head along the axis A (Fig. 2). The steel plate at the bottom of the head was fastened rigidly to the lead safe. The safe and head were inclined at an angle of 20 deg. with the vertical so that their common axis A did not pass through the yoke shown in Fig. 2. A threaded rod was inserted from the top of the head along the axis A, through the tapered hole in the wheel, and threaded into the top of the heavy metal (thread T, Fig. 7). The source was then pulled from the safe up through the tapered hole and into the wheel. The nut N (Fig. 3) was then tightened securely. During the loading process, personnel involved were situated above the head and were shielded from all direct radiation coming up the axis A by the heavy-metal part of the source and by 22 in. of lead in other directions. The loading rod was then unscrewed, and the plug S put into position. The wheel, carrying the source, was then turned to the "off" position. In the loading process certain precautions to be discussed elsewhere were taken to remove the contamination from the outside of the source unit shown in Fig. 7. As an added precaution against the escape of cobalt dust, a sheet of aluminium was placed across the tapered opening at E of Fig. 2 thus sealing the source inside the head.

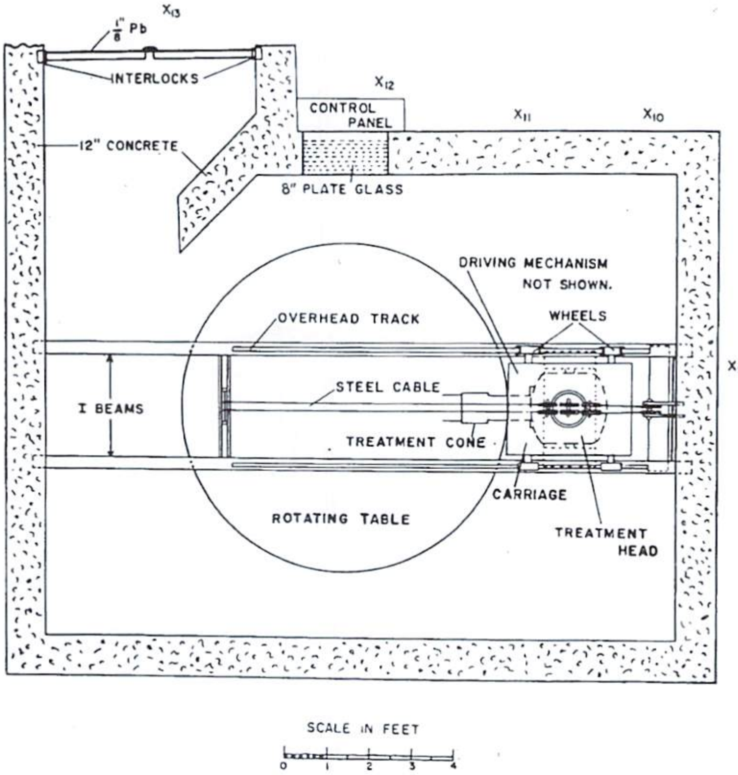

Fig. 5.
Plan view of the treatment room.

Output of the unit

The output of the machine was measured with a 25 r Victoreen chamber placed at 1 metre from the source. For cobalt γ rays a 3-4 mm. wall of lucite surrounding the chamber is required to build up electronic equilibrium. With no additional wall the response of the Victoreen chamber is about 75 per cent. of that obtained with the equilibrium wall. The output of the unit, measured in this way with no collimators in place (field diameter about 30 cm.), is 21·7 r/min. at 1 metre.

The γ rays from cobalt consist of two γ-ray lines of energy 1·17 and 1·33 MeV in equal numbers, emitted in cascade as Co^{60} decays to Ni^{60}. Using an energy flux per röntgen of 3050 ergs/cm^2/r for 1·17 and 3130 ergs/cm^2/r for the 1·33 MeV γ ray it can be shown that the dosage rate 1 metre from a 1000-curie source of cobalt should be 22·8 r/min. This would indicate that the effective strength of the source in our unit is 952 curies. The actual activity of the source may be estimated by applying a number of corrections to this figure. The output of the source is reduced through absorption by the front layers of cobalt of the radiation emitted by the back layers. For this source 75 per cent. of the primary radiation emerges. Self-absorption corrections of this kind have been discussed by Dixon (1951). This reduction in output, however, is partially offset by scattered radiation from the source itself and from the tapered opening in the head. Detailed calculations, to be published elsewhere, show that when once-scattered radiation is included the observed output of this source should be 90 per cent. of the output with no absorption and no scattering. After further corrections are made for attenuation of the beam in the stainless-steel cup, we arrive at a source strength of 1100 curies. This should be compared with 1580 curies as predicted from pile data.

The large discrepancy between these values is hard to explain. Uncertainties in the magnitude of the neutron shielding could not account for more than 5 per cent. of the difference. Some of the source no doubt escaped as dust in the loading process, but it is hard to believe that more than 1 per cent. of the active material would be lost in this way. There is some uncertainty in the value of the effective neutron flux within the pile in the region of the cobalt, where the presence of the cobalt depresses the flux level by an unknown amount. Perhaps the greatest uncertainty is in the selection of an appropriate value for the cross section for pile neutrons. The high-energy neutrons are included in the neutron flux, but they produce little activation of the cobalt. The reduced yield does not come as a surprise to the Isotopes Branch at Chalk River, for they have found from experience that if an activation cross section of 22 barns is used in the calculations good agreement between observed and expected activity is obtained.

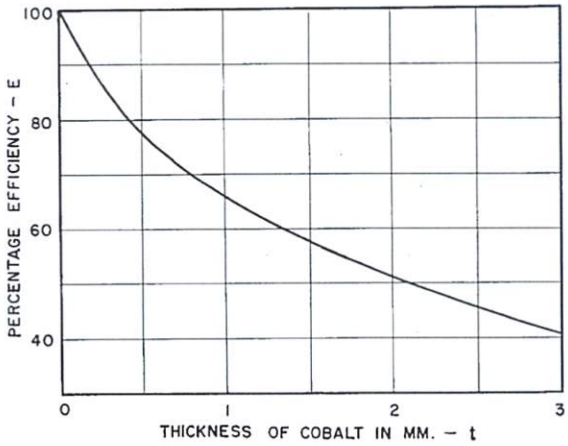

Fig. 6.

Efficiency of irradiation by thermal neutrons as a function of thickness. Efficiency is defined as the ratio of the activity to be expected with shielding to that which would be obtained if there were no shielding.

Stray radiation

Measurements of stray radiation were carried out with a large ionization chamber connected to a D.C. amplifier. The chamber was calibrated with a radium standard. With the cobalt in the "off" position, measurements were made at various points 3 in. from the head. Referring to Fig. 2, the dosage levels at the points X_1, X_2, X_3, X_4, X_5 and X_6, were 8, 1·5, 4·0, 1·5, 13 and 2·8 mr/hr respectively. The dosage levels at X_7 and X_8 (Fig. 3) were 18 and 16 mr/hr. respectively. The worst leak was found in the direction of X_7 (Fig. 3). Measurements were made also at one foot from the head and the dosage rate was found to be less than tolerance (7 mr/hr.) except for the one point X_7 (Fig. 3) at which the tolerance dose was found at a point 15 in. from the head. In the position where the operator would stand to position a patient the dosage level was 1 mr./hr.

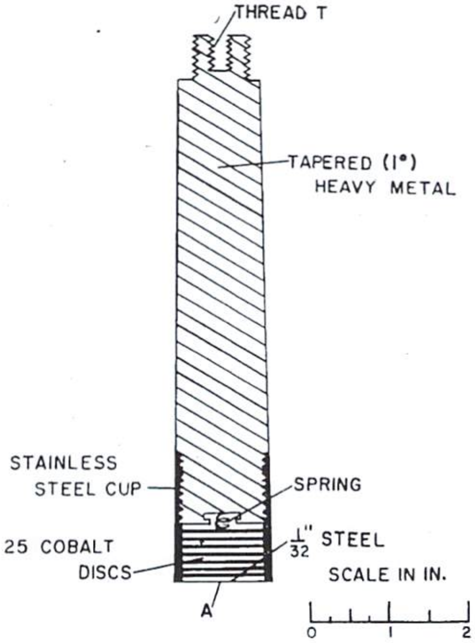

Fig. 7.

Diagram showing the source unit, consisting of a heavy-metal cylinder screwed into a stainless-steel container holding the cobalt discs.

To test the protection provided by the walls of the room the unit was moved over the centre of the rotating table (Fig. 5), and the largest beam obtainable was directed horizontally against a large scattering mass. Measurements outside the room showed that at the points X_9, X_{10}, X_{11}, X_{12} and X_{13} (Fig. 5) the dosage levels were 1, 1·5, 2·5, 4·5 and 6 mr/hr. respectively. In normal operation of the unit, scattering conditions would not be as severe as this, and dosage levels would be correspondingly lower. The oblique concrete shield shown in Fig. 5 was essential to reduce the dosage rate at X_{13} to the tolerance value (6 mr/hr.). In view of the interlocking doors and protective devices, no radiation hazards with the unit are expected.

The design of the treatment fields will be discussed in Paper II. The unit will be used at a source-to-skin distance of 80 cm., where its output is 33 r/min.

Acknowledgments

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II. DEPTH DOSE DATA AND DIAPHRAGM DESIGN FOR THE SASKATCHEWAN 1000 CURIE COBALT UNIT

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Introduction

HIGH energy radiation has two inherent advantages over low energy radiation in the treatment of deep-seated tumours. These are (*a*) the high percentage depth dose resulting from the small attenuation of a high energy beam, and (*b*) the small dose which is given to the skin surface. The design of a therapy unit should be such as to make use of these natural advantages.

Methods for achieving a low skin dose are discussed in this paper. Depth dose data for Co^{60} for a variety of circular fields are presented. The variation of the percentage depth dose with area and with source-to-skin distance is discussed. The effects of the position and thickness of the limiting diaphragm on isodose distributions have been investigated. In the light of this experimental work, suitable treatment cones have been designed.

Surface dose and build-up ratio

When high energy photons interact with matter, most of the resulting electrons are projected in the forward direction. Thus the maximum dose produced by high energy radiation occurs below the surface, at a depth corresponding to the average range of these electrons. For the same reason, as the thickness of the front wall of an ionization chamber exposed to cobalt γ rays is increased, the response increases until a certain maximum value is obtained, after which the response decreases slowly. The ratio of this maximum response to the response with a very thin front wall is called the build-up ratio. With a pure, uncontaminated γ-ray beam the response of a "thin-walled" chamber would be very small, resulting in a large build-up ratio. This ratio has been measured under various conditions with a specially designed thin-walled ionization chamber connected to a D.C. amplifier (Johns, Darby, and Hamilton, 1949). The chamber is a flat cylinder 2 mm. deep and 10 mm. in diameter. The front wall of the chamber consists of a thin layer of cellophane coated with a conducting layer of aquadag. This wall has a total thickness of 2·2 mg./cm.^{2}

A determination of the build-up ratio gives some indication of the contamination of the γ-ray beam with electrons. It is found that many electrons come from the source container and from the tapered hole in the lead treatment head (see Part I, Fig. 2). By covering this hole with a 0·5 mm. aluminium plate, many of these electrons are absorbed and therefore the build-up ratio at a point more than 50 cm. from the source is considerably increased. This effect does not depend critically upon the thickness of the aluminium plate for plate thickness between 0·25 and 1·0 mm. If the aluminium plate is replaced by an equivalent thickness of cardboard or lead