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# THE DEVELOPMENT OF COBALT 60 TELETHERAPY SOURCE PRODUCTION IN AUSTRALIA

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Issued Sydney, October 1962

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## ABSTRACT

A critical assessment is made of relevant data and calculations to determine cobalt 60 production characteristics in a 2V irradiation facility in HIFAR. Significant design features of the irradiation are described, and reasons for their use are given. Results of post irradiation measurements are compared with predictable parameters of neutron flux perturbation and self attenuation of cobalt. A brief description is given of methods used to encapsulate targets, make up the composite source, and install it in its final position. In general, there was good agreement between predicted and observed activities, a distinct feature being the unexpectedly high activation in the lower positions of the irradiation rig. An effective irradiation period of 3220 Mwd thermal reactor power produced specific activities of up to 105 curies per gram of cobalt.

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## 1. INTRODUCTION

In November, 1961 a new 2000 curie cobalt 60 source was installed into a teletherapy unit at St. Vincent's Hospital, Sydney. This operation represented an important stage in the development of radioisotope manufacture in Australia, because the new source was the first one wholly made and assembled in this country.

Examination of the first batch of cobalt 60 withdrawn from HIFAR and of the assembled teletherapy source, showed that the somewhat novel A.A.E.C. technique for producing high specific activity cobalt 60 provided material of the predicted high yield and quality.

Production began in 1959, with the object of producing 20 – 30,000 curies of high specific activity material, and this was achieved in 20 months. The teletherapy source mentioned in this report is only a small fraction of the material now available. It now appears that the A.A.E.C. will be able to enter the general market for high specific activity teletherapy cobalt using techniques which have proved to be satisfactory.

In this report a detailed account is given of the history of production of teletherapy cobalt 60 at Lucas Heights. An outline is given of the composition and post–irradiation handling of the first production rig and assembly of the source.

## 2. TELETHERAPY COBALT 60

The use of cobalt 60 in teletherapy is favoured because its half–life (5.27 years) is conveniently long and because the physical form in which it is available enables sharply collimated radiation beams to be obtained but its main advantage is its usefulness for radiotherapy of deep seated tissue. It is well known that absorption of low energy gamma radiation by the skin and upper tissue layers leads to undesirable side effects but, since a large part of the gamma radiation energy of a collimated cobalt 60 beam is above 1 MeV, the absorption by the upper layers is less than in X–radiation therapy.

Typical cobalt 60 teletherapy sources have activities ranging from approximately 100 to several thousand curies and usually consist of encapsulated cobalt pellets or discs.

The specific activity of the active cobalt should be as high as practicable. This allows sources to be kept relatively small, and this, in turn, helps to reduce self absorption, so that less cobalt 60 is required to reach a given source output. There is also some indication that the extent of energy degradation increases with self absorption (E.L.Hetherington, unpublished data). Further, with a small source, there is relatively small penumbra effect on the fringes of the radiation beam.

Most present demand is for cobalt 60 of approximately 50 – 100 curies/gram and higher specific activity and, in view of the trend towards higher source activities, future requirements will probably be for specific activities of 150 to 200 curies/gram.

Owing to the activation cross section of cobalt 59 and the half–life of cobalt 60, high specific activity material can only be made economically in a high flux reactor such as HIFAR but, even so, irradiation times of the order of 1 to 4 years are required. Since HIFAR was a suitable reactor the Commission undertook cobalt 60 production after development work which made it possible to adopt the irradiation technique described in Section 3.

## 3. DEVELOPMENT OF THE PRODUCTION TECHNIQUE

Since cobalt targets must be irradiated in a high thermal neutron flux for very long periods before it is possible to judge the success of the activation, it was essential to give careful consideration to target size, shape, and canning and to the irradiation technique and equipment to be adopted.

Preliminary calculations and trials, outlined below, led to the adoption of a technique differing from accepted overseas practice. Aluminium encapsulated cobalt discs were immersed directly into the heavy water of HIFAR in simple rigs consisting of the smallest possible amount of aluminium. The orientations of the discs with respect to the core of fuel rods were pre–determined to result in an optimized rate of activation.

### 3.1 Target Shapes and Sizes

Since commercially available teletherapy units use cylindrical source holders, a typical design being shown in Figure 5, A.A.E.C. targets have to be discs of suitable diameter and thickness.

The U.K.A.E.A. produces 17 mm diameter discs, and O.R.N.L. (U.S.A.) and A.E.C.L. (Canada) supply a range of diameters up to 25 mm. The Commission selected 17 mm as one standard. However radiologists generally prefer smaller discs since these make possible the production of more sharply defined beams from the final sources. Therefore to select a second, smaller, A.A.E.C. standard diameter a study was made of the effect of the diameter and thickness of the targets on the yield of cobalt 60.

The high absorption cross section of Co–59 for thermal neutrons suggests that target discs should be thin rather than thick, so that the flux depression within the discs is reduced to a minimum, and maximum activation is achieved. However the thinner a disc is, the greater is the proportion of aluminium to cobalt in a composite teletherapy source. The survey took the form of a lengthy comparative calculation with the following as dependent variables:

(i) activity induced in discs of various dimensions, and

(ii) number of discs required for stacked sources having various outputs.

The levels of the independent variables were:

(i) Nature of neutron flux – wholly axial, wholly isotropic.

(ii) Irradiation periods – 1 and 2 years in an assumed undisturbed thermal neutron flux of $2.5 \times 10^{13}$n cm$^{-2}$s$^{-1}$.

(iii) Disc diameters – 10, 12.5, 15, and 17 mm.

(iv) Disc thicknesses – 1, 1.5, 2, and 2.5 mm.

(v) Stacked source outputs – 250, 500, 750, 1000, 1250, and 1500 curies (effective).

All combinations of these levels were used to calculate data for the dependent variables. The final criterion for accepting a particular disc thickness was the maximum number of discs of the various thicknesses, clad in 24 gauge aluminium and allowing a further 0.6 mm for irregularities, that could be fitted into a source capsule, accommodating a source 45 mm long.

The calculations showed that:

(a) it is largely immaterial whether the neutron flux is wholly axial or isotropic (or of an intermediate nature),

(b) higher specific activities were reached by the thinner discs,

(c) the source outputs that can be reached after 1 and 2 years' irradiation in an assumed flux of $2.5 \times 10^{13}$n cm$^{-2}$s$^{-1}$ follow the pattern given in Table 1.

For one-year irradiations, only small sources could be assembled from 10 and 12.5 mm diameter discs and the effects of self–attenuation and self–shielding owing to increasing disc thickness are not noticeable.

However for two-year irradiations, the 12.5 mm dia. discs allow much larger sources to be stacked than the 10 mm dia. discs. Further, the expected effects of self–attenuation and self–shielding become noticeable for both 10 and 12.5 mm discs (for example, 10 x 1 mm discs allow, but 10 x 2.5 mm discs do not allow, a 500 curie source to be assembled; the same applies to 12.5 x 1.5 mm and 12.5 x 2 mm discs).

It must be emphasized that in the absence of data concerning depressed flux levels along HIFAR's high flux irradiation facilities the above predictions are not absolute. Consequently there is a risk of not achieving the required specific activities, but extension of the irradiation from 2 to 3 years should have the same effect as changing from 1 to 2 years irradiation (see Table 1), that is, give an increased chance of reaching specified source outputs.

The adoption of 1 mm thick discs, rather than thicker ones, could be criticized, in view of their lower mass and the lower activity which can be induced in them. However it can be shown that, in general, a source consisting of several 17 x 1 mm discs has a greater output than one built out of (fewer) 17 x 2½ mm discs, irradiated under the same conditions, since the former are less affected by self-shielding from neutrons.

On stacking canned discs in a source capsule of fixed interior length, the ratio of cobalt to cladding is less favourable for thinner discs. This, however, only becomes critical when specific activities are relatively low. On the other hand use of thicker discs increases the chances of flux depression.

Using these findings and in view of the conservative assumptions made throughout, it was decided to adopt the following standard sizes:

17 x 2.5 mm for rapid production of large sources requiring relatively low specific activity

17 x 1 mm

12 x 1 mm (12.5 mm not being available commercially)

### 3.2 Target Canning

A stock of 17 x 2½ mm, 17 x 1 mm, and 12 x 1 mm high purity cobalt discs was obtained from the General Electric Company at Wembley, Middlesex, Great Britain. Spectrographic analyses of discs selected at random were as follows:

| | |
|---|---|
| aluminium | 100 – 500 p.p.m. |
| chromium | 0 – 20 p.p.m. |
| copper | 100 p.p.m. |
| iron | 20 – 500 p.p.m. |
| magnesium | 100 p.p.m. |
| manganese | 100 p.p.m. |
| nickel | 500 p.p.m. |
| silicon | 500 p.p.m. |
| tin | 100 p.p.m. |
| cobalt | remainder |

To allow the cobalt targets to be inserted into the heavy water, a simple encapsulation method had to be devised because cobalt is known to corrode in water under neutron irradiation. The corrosion products are generally of small particle size, constituting a major contamination hazard in the reactor system if the containment of the target were to become defective. In a series of welding experiments, thin-walled aluminium sheet was pre-formed into two symmetrical dishes and butt-welded to form containers for cobalt discs.

A general arrangement of the welding equipment evolved from these experiments is shown in Figure 1. It was used successfully for the encapsulation of several hundred cobalt discs. A conventional lathe was geared down at the main drive to a range of 10 – 20 r.p.m. Two pre-formed dishes made of ½ mm thick aluminium sheet, containing the cobalt target, were placed against each other with their open ends forming a continuous butt joint. The assembly was centred between two copper bars which positioned it and acted as heat sinks during the welding operation. The argon arc welding process was used, with a $^1/_{16}$ inch dia. thoriated tungsten electrode and an argon flow rate of 8 litres per minute. Welding speed and heat input were carefully controlled. Welded assemblies were subjected to 5 day immersion tests in N/1000 nitric acid followed by spectrographic analysis of the solution to detect escaped cobalt. The best welding results were obtained at a heat input corresponding to 35 – 38 amps, an open circuit voltage of 52 volts, the use of high frequency surge injection, and a welding speed of

15 r.p.m. A standard commercial welding machine had to be modified to achieve the closely controlled low heat input stated.

Type F57 S aluminium was used as canning material. Its typical composition was

| | |
|---|---|
| iron | 0.12% |
| silicon | 0.07% |
| copper | 0.01% |
| manganese | 0.01% |
| magnesium | 1.25% |
| aluminium | remainder |

## 4. THE IRRADIATION METHODS

### 4.1 Principle

Immersion of canned cobalt discs in the heavy water of HIFAR overcomes the following disadvantages of the more usual irradiation methods in which the target discs are incorporated in a metal rig which isolates them from the heavy water:

> Many rigs of conventional design incorporate large amounts of Zircalloy or stainless steel, Both materials are stronger neutron absorbers than aluminium and consequently cause a greater reduction in neutron flux reaching the target discs. Additional unwanted nuclear heating requires the provision of a secondary cooling circuit and warning devices to guard against the possibly hazardous effect of interruptions of the coolant flow.
>
> For complicated rig designs the geometrical position of the moderator relative to the target is comparatively remote; this may reduce the efficiency of neutron thermalization near the targets and thus affect the total neutron flux useful for the activation point.

The rig for immersing the cobalt in the heavy water consisted essentially of an open-ended tube supporting carrier boxes for canned discs. A photograph of a cutaway model is shown in Figure 14. By perforating the reactor thimble, heavy water was allowed to come into contact with the discs assuring effective removal of the heat generated in the cobalt by neutron capture, beta and gamma decay, and the reactor gamma flux.

For economy, the rig was designed to be used in both trial and full term irradiations. A certain flexibility was required in order to allow the loading pattern to be changed at will, since the main purpose of the trial irradiations was the determination of optimum disc orientations with respect to the core.

### 4.2 Irradiation Rigs

The rigs were attached to standard HIFAR 2V shield plugs, and consisted of an open ended outer aluminium carrier tube holding seven rectangular disc-carrying boxes. The carrier tubes, made of 16 gauge aluminium, had an outer diameter of approximately 1¾ inches and were approximately 5 feet long. At either end the carrier tube was provided with a number of ½ inch diameter perforations, which allowed free access of heavy water to the carrier boxes.

Each box was approximately $^{15}/_{16}$ inch by $^{13}/_{16}$ inch by 6 inch and carried a number of canned cobalt discs standing in positioning slots. The sides of the boxes were concave to facilitate water flow through the interior of the rig. For firm support of the boxes along the carrier tube of the rig an inner tube of rectangular cross section was welded to the inner wall of the carrier tube.

To load the rig, boxes were charged with discs and slid along the inner tube. The rig was then attached to the shield plug and finally a Chromel/Alumel thermocouple, magnesium oxide insulated and stainless steel sheathed, was led through the plug and along the carrier tube to terminate just below the heavy water level.

Various features of the irradiation such as the spacing between discs and the angles of the discs with respect to the vertical could be varied by proper design of the disc positioning slots in the boxes. Similarly, the mass and distribution of cobalt on the rig could be changed at will by leaving selected slots or boxes empty. Hence this design was readily suitable for trial irradiations of rigs as described in Section 4.3.

### 4.3 Trial Irradiations

In the absence of any data on cobalt disc activation other than studies based on unproved assumptions such as isotropic neutron flux and negligible scatter within the absorber, (Lewis 1955, Ayers and Lewis 1958), it was impossible to make realistic predictions of total and specific activities, or of the irradiation times required for given outputs of teletherapy cobalt 60.

Since it was particularly necessary to avoid premature rig withdrawal in actual production operations, measurements were made of depressed neutron flux levels along the various 2V irradiation facilities allocated to cobalt 60 production. This was done by loading rigs with cobalt, submitting them to short activations at low reactor power, removing the rigs from the shield plugs, and withdrawing selected cobalt discs for activity determination by counting.

There are, however, several features of the loading which affect the depressed flux levels and hence the rate of activation of cobalt. One is the spacing between discs (Lewis 1955, Eastwood et al. 1958, Ayers and Lewis 1958). A target inserted into a neutron flux acts as a "sink" which produces a flux gradient. For maximum activation it is clearly important to place discs outside neighbouring sinks. Measurements in DIDO (Eastwood et al. 1958) demonstrated the magnitude of the sink effect, but the data refer to 17 x 2.5 mm discs and are not applicable to other sizes.

Another point which is also best decided experimentally, is the effect that changing the total rig loading has on the rate of activation. A loaded rig as a whole may be regarded as a neutron sink, so variations in the mass of cobalt on a rig must be expected to affect the depressed flux. A calculation of the magnitude of this effect could be exceedingly complex, but direct measurements readily yield the desired information.

It is of interest to discover whether leaving the centre of the rig empty leads to an appreciable flux recovery on either side of the gap. Finally it is desirable to discover whether or not the neutron flux is isotropic. If the flux has a directional component or current, then positioning discs so as to face this current should result in best activation. Even though the direction of the current is not known, its effects can be determined indirectly by trial irradiations with discs having various inclinations with respect to the core.

A short experiment was designed to investigate these variables in a small number of trial irradiations. The independent variables (or factors) chosen were as follows, the data in brackets being the "levels" used:

- 2V irradiation facility (2V2, 2V4, 2V5, and 2V9)
- Disc diameters (12 mm and 17 mm)
- Spacing between discs (4 mm and 8 mm)
- Gap in centre of rig (box 4 loaded, box 4 empty)
- Angle of discs to horizontal plane (0, 45, 90, and 135°)
- Angle of discs to vertical plane (0, 45, 90, and 135°)

A full "factorial" experiment, that is, a trial of every possible combination of the above factors at the values shown, would require $2^9$ irradiations, but adequate information can be obtained from a fractional replicate of the factorial experiment. The experiment was reduced to 32 separate trial irradiations. In order not to bias the results the fractional replicate was chosen by the methods of Brownlee (1949).

The dependent variables were the activities induced in the centre disc of each box, measured under standard conditions, normalized to one standard value which corresponded to the average number of kilowatt minutes of all trial irradiations, and then transformed to (a) depressed flux levels, and (b) specific activities per unit reactor power and time.

The trial irradiations were carried out in 8 sets, each set consisting of four irradiations in the respective four 2V holes. Typical examples of the 32 experimental conditions were as follows:

(1) 2V2, 17 mm, 8 mm, box 4 empty, 45°, 135°.

(2) 2V5, 12 mm, 4 mm, box 4 empty, 0°, 45°, etc.

For a typical set of irradiations, the four rigs used were loaded with 6 boxes according to the experimental plan; box 7 contained four 17 x 2½ mm reference discs. The rigs were inserted into the four holes, irradiated for a few minutes at approximately 2.5 kW reactor power (thermal), withdrawn, and allowed to decay for 20 minutes. They were then dismantled, the sample discs were removed for activity measurement and the loading of the rigs was modified to suit the next set of irradiations.

Experimental results were submitted to six separate "analyses of variance", that is, one analysis for each of the six boxes. These analyses showed whether the 31 possible effects and interactions were significant.

Many main effects and interactions were found to be significant, although many were relatively small. Some of the more important ones were:

- The depressed neutron flux levels in the four holes differed. This effect is largely independent of the rig loading, but also interacts with the actual loading.
- Increase of the mass of cobalt on a rig (both by replacing 12 mm by 17 mm diameter discs and by decreasing the inter-disc spacing) causes a decrease in the specific activity induced. However, doubling of the mass decreases the specific activity by only about 20 per cent.
- The presence of an empty gap at the centre of a rig results in a significant increase of the specific activity at either side of the gap, but the effect decreases rapidly with distance from the gap and does not make up for the reduced rig loading.
- For maximum activation all discs must be positioned vertically in the respective irradiation holes. Figure 13 shows the disc orientation relative to the centre of the reactor core for the four 2V positions investigated.

In addition to the above results, the variation of the depressed flux along each hole for a variety of loadings was deduced from the activity measurements. For all four holes the flux reached the maximum 5 – 10 inches below the horizontal centre line of the rig but its distribution about this line was not symmetrical.

Optimum rig loadings for each hole were then determined and induced activities were predicted for irradiations at full reactor power for 1, 2, and 3 years. However the loadings used for actual full term irradiations were not necessarily those indicated by the trial irradiations, owing to other considerations such as the need to obtain a large activity in thick discs rather than thin ones.

Full details, especially of experimental design and statistical treatment of the results, are to be provided in other reports. Details of rig loadings are given in Rig Operating Manuals. However, the loading of Rig X-15, the first one withdrawn, is given in Table 2.

## 5. POST IRRADIATION EXAMINATION AND MEASUREMENT

The first irradiation rig (X-15) was withdrawn and unloaded successfully in a high activity handling cell during November 1961. The detailed checks and measurements made are reported here because the information gained will be valuable for future rig withdrawals.

### 5.1 Dismantling of Rig

The shield plug/rig assembly was introduced into a high activity handling cell by the standard method. The rig was separated from the plug by cutting it just below its upper end. The carrier boxes were pushed from the rig (Figure 6) and the discs were removed from the boxes and checked individually.

### 5.2 Dimension Checks

Cobalt and aluminium are dimensionally stable under irradiation conditions. However, as several canned cobalt discs, which had a nominal diameter of 20 mm, were to be stacked in a teletherapy source capsule having an inner diameter of between 20.0 and 20.5 mm, any sizeable build-up of an oxide layer on the surfaces of the cans could cause jamming during the stacking operation.

Therefore all discs were put through annular gauges, stepped from 19.5 to 21.0 mm and sorted into several size groups. It was found that the oxide layer on the aluminium cladding was not thick enough to cause trouble; (see Figure 2).

### 5.3 Checks for Escaped Cobalt

Swab samples were taken from each disc and counted in a 1 inch dia. end-window G.M. tube. Count-rates ranged from 15 to 70 counts per second, values commonly found for any aluminium surface after prolonged irradiation in the heavy water circuit of HIFAR. The gamma spectra of several of the swab samples showed no evidence of cobalt 60 in the contamination.

### 5.4 Measurement of Disc Activities

Measured activities were expressed in terms of "effective activity", which is of more interest to the user than total activity of discs or source.

To determine "effective activities", the dose rates at a distance of 1 metre from the discs, were found with a Farmer reference condenser ionization chamber, by exposing the charged chamber to each source within the handling cell for a given period, and determining the voltage drop using an electrometer outside the cell. The "effective activities" at one metre were calculated by dividing dose rates by the K-factor for cobalt which is 1.35 $r\ h^{-1}\ c^{-1}$. They are listed in Table 2 and are also shown in Figure 3.

Dosemeters used for these measurements were calibrated against similar equipment used at St. Vincent's Hospital, Sydney. The latter equipment had been standardized at the NPL, Teddington and was known to have given measurements of an A.E.C.L. cobalt 60 source in agreement with those obtained by the National Research Council, Canada.

## 6. ASSEMBLY AND INSTALLATION OF A STACKED TELETHERAPY SOURCE

Several of the discs, obtained from unloading the first cobalt rig to be withdrawn, were assembled into a teletherapy source which was to replace a partly spent one installed at St. Vincent's Hospital, Sydney. The following description of source assembly and changeover is given here, because the experience gained is valuable for future operations. The work was done in a high activity handling cell.

### 6.1 Encapsulation of Source

Figure 5 is a schematic drawing of a sealed stainless steel capsule which is designed to house a stack of discs. The cylindrical capsule has a "window" of 0.020 inch thick stainless steel and consists basically of an inner and an outer can. Each can may be closed by screwing plugs against metal O-rings, applying a torque of about 20 foot pounds. This may be done by remote control.

A perlitic stainless steel spring washer placed against the plug of the inner can is kept under compression by the plug of the outer can. This prevents the plug of the inner can from becoming unscrewed.

### 6.2 Source Assembly

After measuring the effective activity of each disc using a condenser ion-chamber, the teletherapy source was assembled. (Figures 7 and 8). Eight cobalt discs were stacked into a stainless steel capsule. Discs were selected on the basis of suitable activities and their total activity was approximately 2600 curies.

While other work was done in the cell, the source was kept in a 4 inch lead castle previously set up in the cell and intended to prevent damage to the zinc bromide window. The surface temperature of the castle rose by about 20 °F from the combined effect of source decay and radiation absorption by the lead walls.

### 6.3 Selection of Discs for Source Stacking

The specifications for a teletherapy source usually refer to the source "output" or to its effective activity. The output is the effective strength of gamma emission from the base of the cylindrical source facing the object to be irradiated and is expressed in terms of a dose-rate, for example, roentgen per minute at a metre distance (rmm), or similar expressions. Effective activity is the activity which an idealized point source of cobalt 60 at the point of consideration must have, to produce the same dose-rate. It is expressed in "effective curies".

Even small teletherapy sources have relatively large physical dimensions and cobalt effectively attenuates cobalt 60 radiation, so the self-absorption of a source must be known before source output, or effective activity, can be derived from the total number of curies constituting the stacked, cylindrical source. For a homogeneous line source the effective activity A (Fano 1953, Rockwell 1956) is given by

$$A = \frac{A_0 \exp(-\mu L)}{2} \int_{-L}^{+L} \exp(-\mu x)\left(1 - \frac{x}{a}\right)^2 dx \quad , \qquad (1)$$

where A = the total activity measured at a point P at a distance a from the centre point of the linear source,

$A_0$ = activity unaffected by self absorption (curies),

$\mu$ = linear absorption coefficient for Co-60 gamma radiation of the source material (i.e. cobalt) ($\text{cm}^{-1}$),

2L = length of cylindrical source (cm), and

x = distance between the longitudinal centre of the source and a radiation emitting element in the source (cm).

By integrating (1), A may be written

$$A = A_0 e^{-\mu L}\left(1 + \frac{\mu^2 L^2}{6}\right) , \qquad (2)$$

to a very high degree of approximation. This relation has been verified empirically (E.L.Hetherington A.A.E.C. Report in press).

Selection of discs for the teletherapy source was made by using Equation 2 putting L equal to 0.5 inches and $\mu$ equal to 0.45.

The above relationship is based on the assumption that the stacked source is homogeneous, but in practice, component discs have different activities. Since an analytic treatment of self-absorption in non-homogeneous sources would be extremely laborious the optimum stack configuration was determined empirically. The work, reported by Hetherington, shows that maximum radiation output with minimum energy degradation is obtained only if the discs are stacked in ascending order of activity with the most active disc at the "patient" end of the source.

### 6.4 Packing of Source and Source Installation

The source was used to replace another, partly spent, source installed in an Atomic Energy of Canada Ltd. (A.E.C.L.) teletherapy head (known as a Theratron) so it had to be inserted into the drawer of a combined transport/transfer container which allows withdrawal of the spent source and insertion of a new one into the head.

The transfer container designed and built by A.E.C.L., is provided with channels for two tungst drawers (see Figure 9), each of which may be loaded with a source of up to 3000 curies. The drawer dimensions are about 3 x 3 x 19 inches.

To exchange sources, the transfer container (holding only one drawer) is placed against the head (Figure 10), the spent source in its own drawer is withdrawn into one of the channels and the drawer holding the new source is then charged into the head (Figure 11). These operations are shown schematically in Figure 12. The exchange of sources at St. Vincent's Hospital was carried out by R.K.Treloar, agent for A.E.C.L.

It should be noted that during both pull-through operations, (that is, from head to container and vice versa) each source is momentarily exposed while passing the gap between head and container. The operator normally stands behind the lead-filled dummy-drawer and is adequately shielded but exceedingly high dose-rates may be observed for a fraction of a second in the direction at right angles to the dummy drawer.

### 6.5 Output of Installed Source

Final source output measurements were made using a sub-standard Baldwin Dosemeter after the source was installed. The dosemeter was placed at the centre of rotation of the teletherapy head, corresponding to a nominal distance of 75.0 cm between dosemeter and source "window". (Later checks showed that the distance varied from 74.90 to 75.35 cm because the path described by the rotating "head" was elliptical.

The dosemeter was exposed to the radiation beam several times for periods between 30 and 60 seconds. Repetitive exposures with the beam radiating horizontally and vertically were made to average out any errors due to radiation scattered by the treatment table and floor and walls of the shielded treatment room. However it was found that exposures made when a lead sheet was placed behind the dosemeter to attenuate any scattered radiation, gave identical results. Therefore the measurements had been unaffected by scatter.

Dose-rates measured in both the horizontal and vertical directions were averaged, corrected to their value at a standard distance of 1 metre between the centre of the source and the centre of the dosemeter, a standard temperature of 20 °C, and a standard atmospheric pressure of 760 mm of mercury. The value obtained was 34.9 r/min which may be compared with the value of 35.0 r/min calculated from the individual disc activities and corrected for self-absorption (see Table 2). It was within the user's specification for the source, which was 30 - 40 r/min at 1 metre.

## 7. DISCUSSION AND CONCLUSIONS

### 7.1 The Canning Method

By June 1962 42 discs had been immersed in the reactor heavy water for 3220 megawatt-days and a total period of approximately 525 calendar days, and a further 231 discs for an average of 4407 megawatt-days and 437 calendar days.

Frequent checks of heavy water samples from HIFAR gave no indication of cobalt 60 activity and the swab tests on each of the 42 discs withdrawn from HIFAR were negative. This shows conclusively that the canning technique and the pre-irradiation inspection of the cans were satisfactory.

Some observers had claimed that diffusion of cobalt 60 through the aluminium capsule can occur during irradiation. There is absolutely no evidence of this in these irradiations. The efficient cooling may be an important factor in preventing any diffusion, which in any case may have been confused with leakage through canning defects.

### 7.2 The Irradiation Method

The activities of the discs produced on the first rig withdrawn in September, 1961 showed that the average rate of activation was highly satisfactory. This rate agreed substantially with values predicted by extrapolation of the results of the trial irradiations and compared favourably with what is known of overseas practice, which involves isolation of cobalt from the heavy water moderator.

### 7.3 The Irradiation Rigs

The A.A.E.C. cobalt rig is simple, efficient, and economical. The manufacturing cost of a rig of this type, excluding the shield plug, was approximately £A150 which amounted to only about 1 per cent. of the value of cobalt 60 produced in it.

Experience in the handling of the rig during the low power trial irradiations, the assembly of several rigs, and the dismantling of the first rig, showed the great ease with which cobalt discs in a variety of spacings and orientations may be loaded and removed from the rig.

The same type of rig has also been used successfully for the activation of radiography sources, and it will be useful in a wide range of high flux irradiations.

### 7.4 Low Power Trial Irradiations

The primary purpose of the trial irradiations was to determine the depression of flux levels so that optimum loading of the rigs could be arranged to meet current commitments.

Prediction of induced activities by far-reaching extrapolation from the results of low power irradiation was uncertain and only a secondary purpose. It pre-supposed that reactor conditions were identical in low power and long term irradiations and this cannot be ensured in a research reactor. However the predictions were a useful guide and substantially accurate.

### 7.5 Long-Term Irradiations in Rig X-15

The effective activities of the 42 discs from rig X-15 are listed in Table 2 and also shown in Figures 3 and 4.

In Figure 4 the predicted and observed results are compared and the following observations may be made:

(a) There is a minimum in the curve corresponding with the level of boxes 4 and 5. It should be noted that boxes 4 and 5 had each been loaded with six 17 x 2½ mm discs, whereas predicted values referred to lesser box loadings of thinner (1 mm) discs. This minimum is caused by the presence of a greater mass of absorber in the lesser state of the subdivision.

(b) The maximum activation was achieved, not in the centre boxes, which correspond to the horizontal centre line of the reactor core, but in box 7 which was well below this line. This may have been due to the fact that for most of the irradiation period the reactor fuel burn-up was lower than expected. This implies that the coarse control arm angles were small and tended to displace the peak flux region to a lower area in the reactor. The same result could arise from the differing reactor loading conditions which existed at low and full power irradiations.

(c) The activities produced in boxes 2, 3, 6, and 7 were greater than expected. This was only explained by further consideration of the results of trial irradiations. The trials constituted a multi-factor experiment whose results were used to determine optimized rig loading patterns. It was shown, for example, that vertical discs would be activated more rapidly than horizontal ones and that increased spacing between discs would result in faster activation. The predictions assumed that these effects were only additive but it is now known that they interacted as well, producing results better than expected. It is normally possible in factorial experiments to determine the additivity or otherwise of significant effects but the necessary fractionation of the experiment to limit the number of trial runs as noted in Section 4.3 made this impossible.

(d) There was good agreement near the centre of the rig, that is on boxes 4 and 5.

The closeness of observed and predicted activities must be considered to be incidental but the main purpose of the low power experiments in determining conservative output figures was achieved.

### 7.6 Activity Measurements and Output of Composite Teletherapy Sources

Finally the intensity of the emitted radiation at a given distance is one of the most important features of a teletherapy source. Prediction of the radiation intensity from the activities of the individual discs is complicated by:

(a) the uncertainties of self-absorption within the source, especially if the source is not homogeneous, and

(b) the degradation and the build-up of radiation owing to source containment in, and collimation by, the teletherapy head.

The output of a stack of discs may be predicted from the activities of the component discs by using Equation 2 of Section 6.3, provided that the linear absorption coefficient of the source material is known. But the results are affected by errors in measurement of component disc activities in a shielded handling cell, where the effects of radiation scatter may be different. The effects of source holder design and diaphragm, collimation and shutter geometry (which differ in various heads) on radiation degradation and build-up are too numerous to permit standard treatment. The only way to overcome the variation between heads is to make use of fully standardized geometrical conditions in a measuring device, a matter on which the International Atomic Energy Agency has recently made practical proposals (Kemp et al. 1962).

## 8. ACKNOWLEDGMENTS

The authors wish to acknowledge the excellent assistance of staff members associated with this project, and in particular Mr. F. Bett, who was responsible for the disc encapsulation welding method, Mr. N. Holt, the project engineer, Mr. P. T. Rafter who assisted with the irradiation trials, and Dr. J. N. Gregory for his encouragement and many useful suggestions.

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## TABLE 1

### FEASIBILITY OF REACHING SOURCE OUTPUT BY USE OF VARIOUS COMPONENT DISCS

| | | IRRADIATION TIME | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 year in 2.5 x $10^{13}$n $cm^{-2}$ $s^{-1}$ | | | | | | | | | | | | | | | | 2 years in 2.5 x $10^{13}$n $cm^{-2}$ $s^{-1}$ | | | | | | | | | | | | | | | |
| | | DISC DIAMETER | | | | | | | | | | | | | | | | DISC DIAMETER | | | | | | | | | | | | | | | |
| | | 10 mm | | | | 12.5 mm | | | | 15 mm | | | | 17 mm | | | | 10 mm | | | | 12.5 mm | | | | 15 mm | | | | 17 mm | | | |
| Disc Thickness (mm) | | 1 | 1.5 | 2 | 2.5 | 1 | 1.5 | 2 | 2.5 | 1 | 1.5 | 2 | 2.5 | 1 | 1.5 | 2 | 2.5 | 1 | 1.5 | 2 | 2.5 | 1 | 1.5 | 2 | 2.5 | 1 | 1.5 | 2 | 2.5 | 1 | 1.5 | 2 | 2.5 |
| Source Output in Effective Curies | 250 | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| | 500 | – | – | – | – | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | – | + | + | + | + | + | + | + | + | + | + | + | + |
| | 750 | – | – | – | – | – | – | – | – | + | + | + | + | + | + | + | + | – | – | – | – | + | + | + | + | + | + | + | + | + | + | + | + |
| | 1000 | – | – | – | – | – | – | – | – | – | – | – | – | + | + | + | + | – | – | – | – | + | + | + | + | + | + | + | + | + | + | + | + |
| | 1250 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | + | + | – | – | + | + | + | + | + | + | + | + |
| | 1500 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – | + | + | + | + | + | + | + | + |

\+ Source can be assembled from discs

– Source cannot be assembled from discs

# TABLE 2

## MEASURED Co–60 ACTIVITIES AFTER 320 DAYS EFFECTIVE IRRADIATION AT 10 MW POWER

| Distance From the Horizontal Centre Plane of Reactor Core (inches) | Ident No. | Size of Target | Mass of Target (grams) | Total Effective Activity (curies) | Specific Activity (curies per gram) |
|---|---|---|---|---|---|
| 19 | 20 | 17mm dia. x 2.5mm | 4.75 | 120 | 25 |
| 18 | 12 | " " | " | 98 | 20 |
| 17 | 11 | " " | " | 147 | 31 |
| 16 | 44 | " " | " | 130 | 27 |
| 15 | 05 | " " | " | 140 | 29 |
| 14 | 21 | " " | " | 152 | 32 |
| 13 | 218 | 17mm dia. x 1mm | 2.0 | 98 | 49 |
| 12 | 105 | " " | " | 98 | 49 |
| 11 | 238 | " " | " | 116 | 58 |
| 10 | 119 | " " | " | 116 | 58 |
| 9 | 199 | " " | " | 126 | 63 |
| 8 | 100 | " " | " | 133 | 66 |
| 7 | 185 | " " | " | 155 | 78 |
| 6 | 160 | " " | " | 150 | 75 |
| 5 | 223 | " " | " | 148 | 74 |
| 4 | 233 | " " | " | 153 | 76 |
| 3 | 187 | " " | " | 155 | 78 |
| 2 | 143 | " " | " | 176 | 88 |
| 1 | 47 | 17mm dia. x 2.5mm | 4.75 | 280 | 59 |
| 0 | 16 | " " | " | 290 | 51 |
| –1 | 13 | " " | " | 300 | 63 |
| –2 | 25x | " " | " | 310 | 65 |
| –3 | 28x | " " | " | 311 | 65 |
| –4 | 23x | " " | " | 317 | 67 |
| –5 | 33 | " " | " | 306 | 61 |
| –6 | 30x | " " | " | 315 | 63 |
| –7 | 40x | " " | " | 338 | 67 |
| –8 | 26x | " " | " | 330 | 66 |
|  |  |  |  |  | (continued) |

**TABLE 2** (continued)

| Distance From the Horizontal Centre Plane of Reactor Core (inches) | Ident No. | Size of Target | Mass of Target (grams) | Total Effective Activity (curies) | Specific Activity (curies per gram) |
|---|---|---|---|---|---|
| −9 | 18x | 17mm dia. x 2.5mm | 4.75 | 352 | 70 |
| −10 | 06x | " " | " | 360 | 72 |
| −11 | 147 | 17mm dia. x 1mm | 2.0 | 190 | 95 |
| −12 | 69 | " " | " | 200 | 100 |
| −13 | 84 | " " | " | 193 | 96 |
| −14 | 08 | " " | " | 193 | 96 |
| −15 | 73 | " " | " | 183 | 92 |
| −16 | 01 | " " | " | 194 | 97 |
| −17 | 74 | " " | " | 210 | 105 |
| −18 | 07 | " " | " | 176 | 88 |
| −19 | 87 | " " | " | 190 | 79 |
| −20 | 48 | " " | " | 135 | 67 |
| −21 | 51 | " " | " | 113 | 56 |
| −22 | 90 | " " | " | 105 | 51 |

x denotes discs used to make up the teletherapy source.

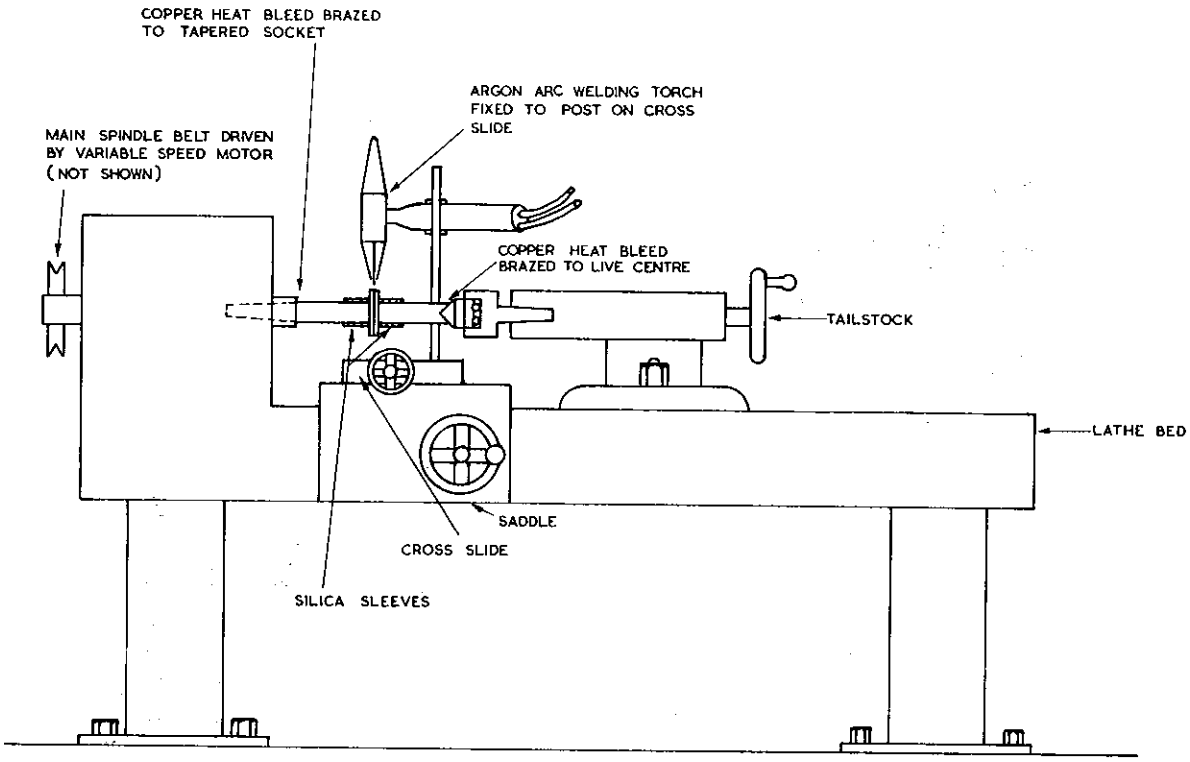


FIGURE 1 SCHEMATIC LAYOUT OF WELDING EQUIPMENT USED FOR THE ENCAPSULATION OF COBALT DISCS.

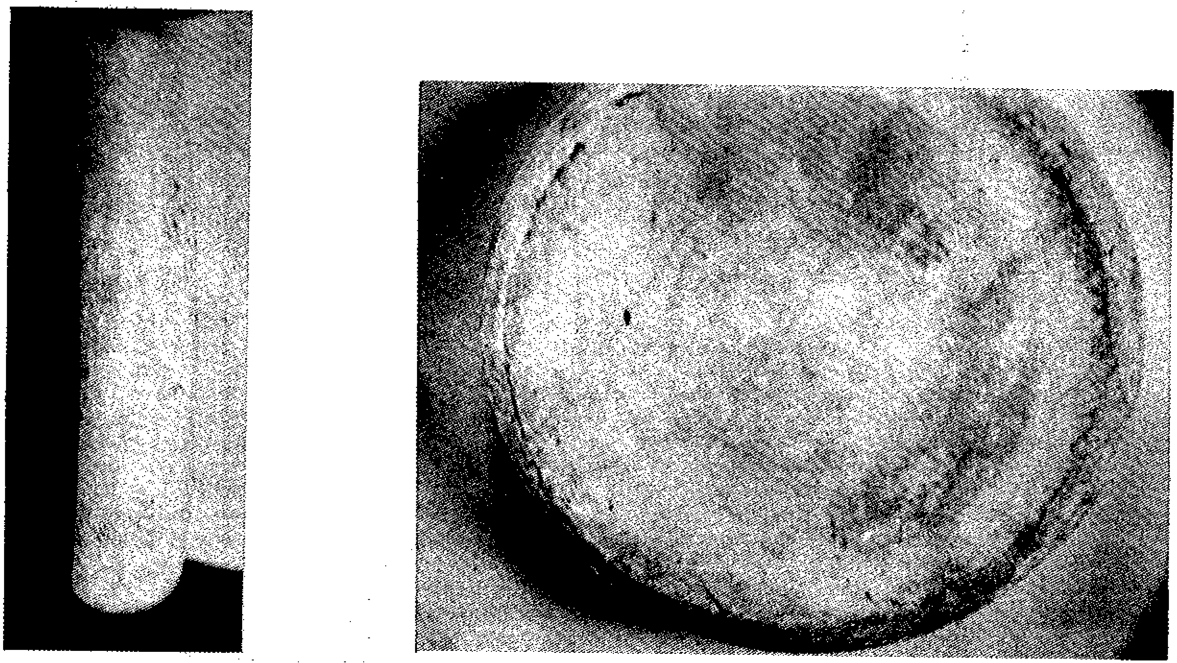


FIGURE 2 MAGNIFIED PHOTOGRAPH OF AN ALUMINIUM ENCAPSULATED COBALT DISC, 17 mm DIA. BY 2.5 mm THICK AFTER IRRADIATION IN A NEUTRON FLUX OF THE ORDER OF $1.9 \times 10^{21}$nvt.

Black spots are thin deposits of aluminium oxide. The pitting effect visible along the dividing line of weld and parent metal was found to be of insignificant depth.

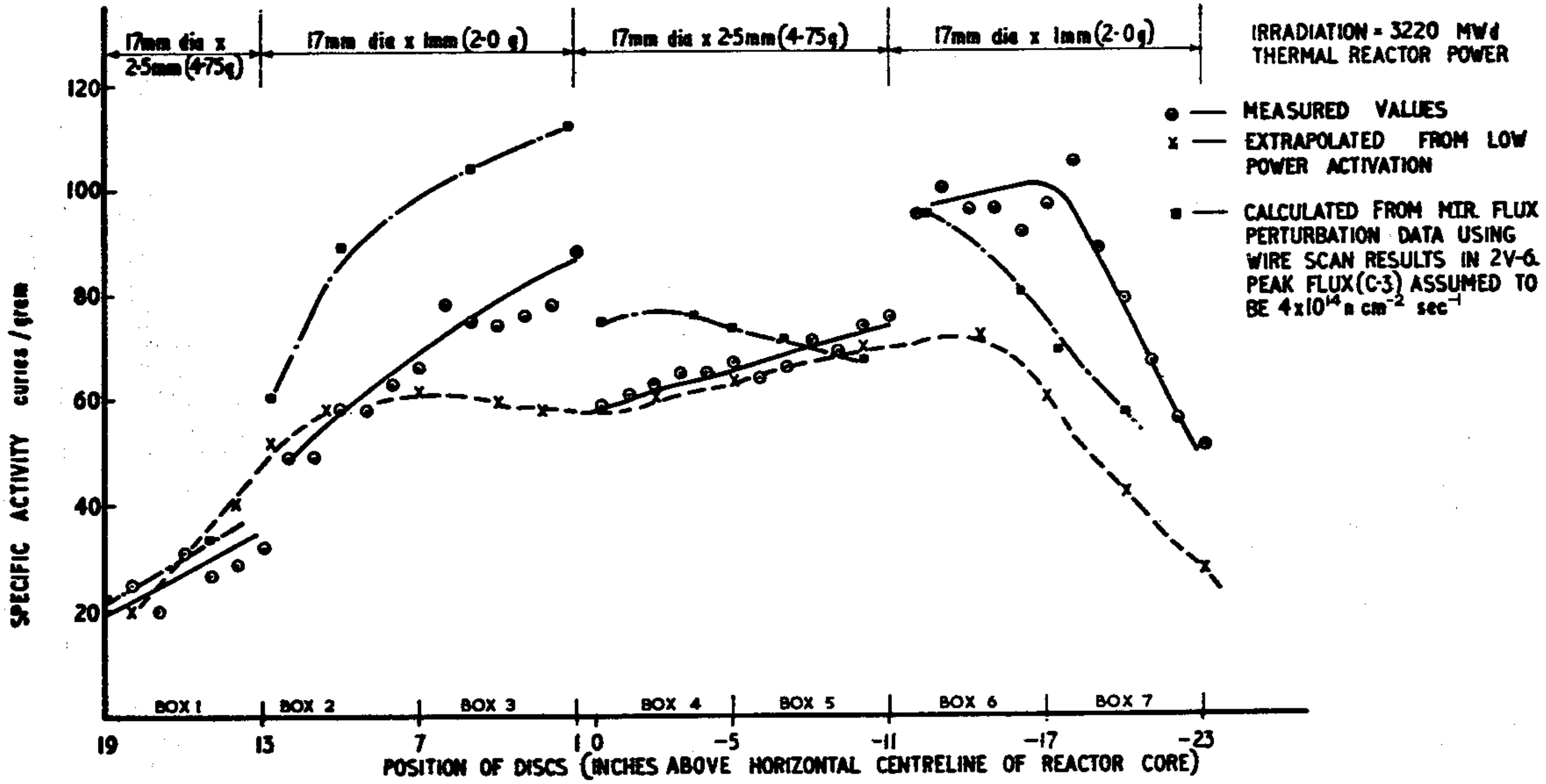


FIGURE 3 MEASURED SPECIFIC ACTIVITIES OF IRRADIATED COBALT DISCS COMPARED WITH CALCULATED VALUES

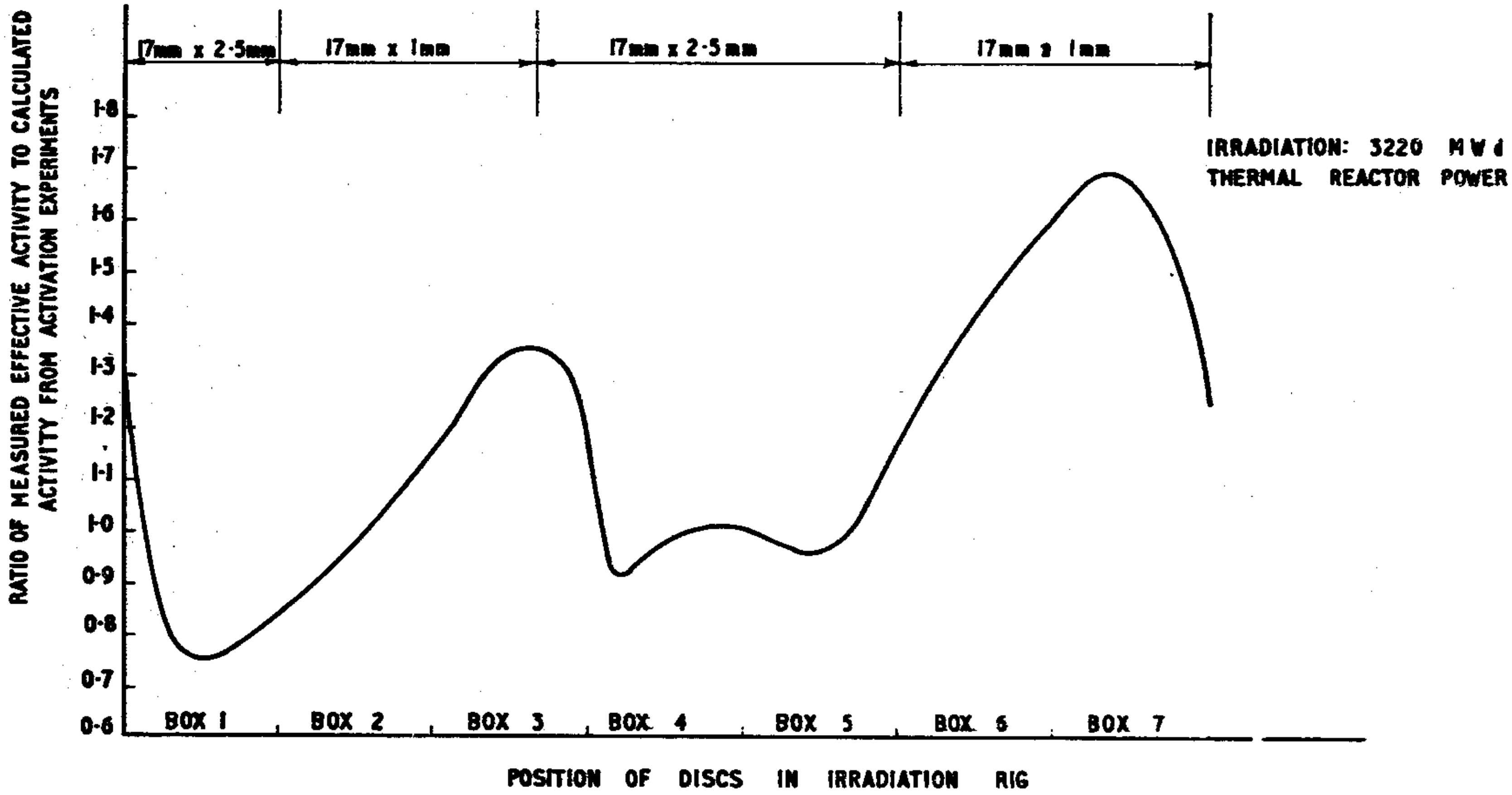


**FIGURE 4** RATIOS OF ACTUAL AND PREDICTED SPECIFIC ACTIVITIES AFTER IRRADIATION IN THE 2V–5 FACILITY

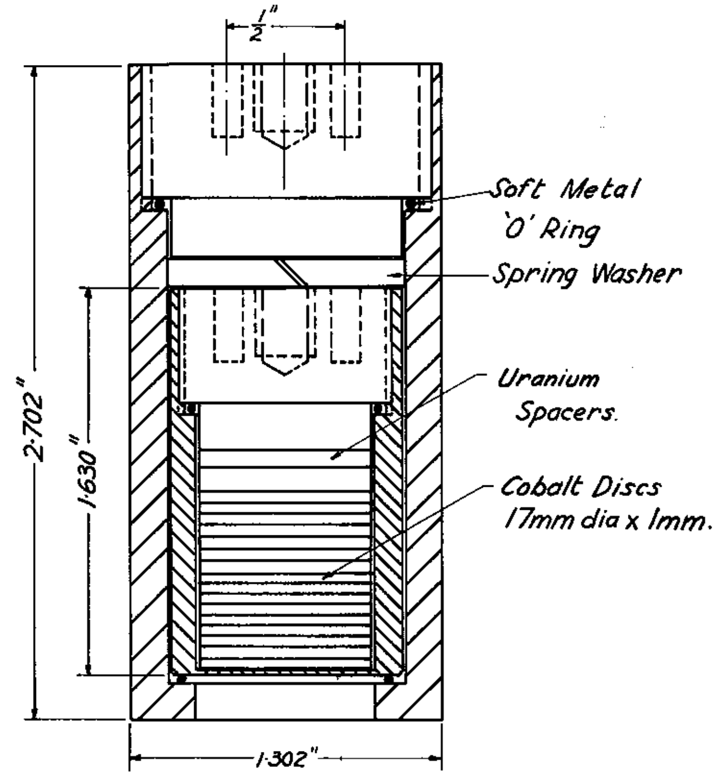


FIGURE 5 ENCAPSULATION OF Co–60 TELETHERAPY SOURCE.

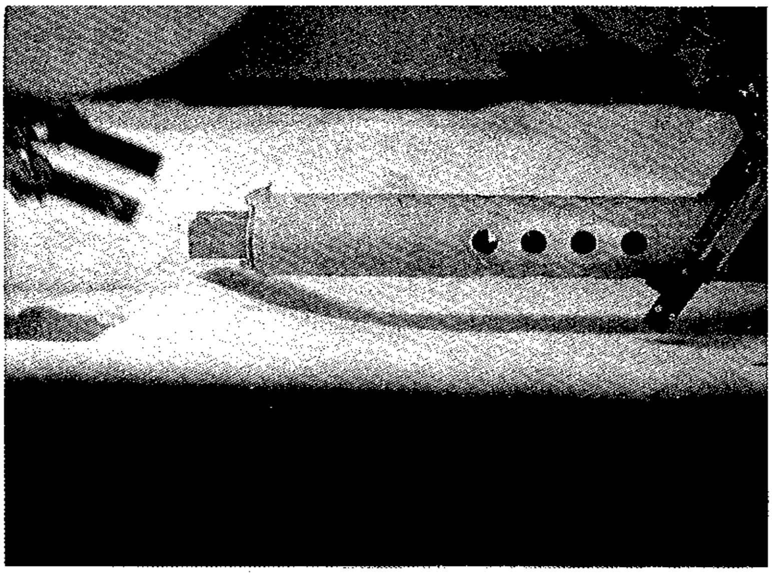


FIGURE 6 WITHDRAWAL OF ALUMINIUM BOX CONTAINING IRRADIATED COBALT DISCS FROM THE CARRIER TUBE OF THE IRRADIATION RIG.

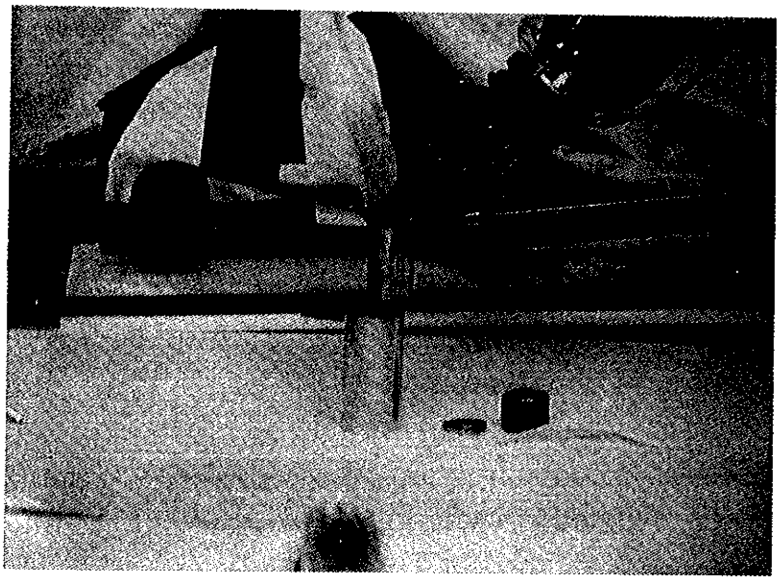


FIGURE 7 PLACING SEALED INNER CAN CONTAINING THE COMPOSITE SOURCE INTO THE OUTER CAN OF THE SOURCE CONTAINER ASSEMBLY.
(Plug and spring washer for the outer can is in the foreground).

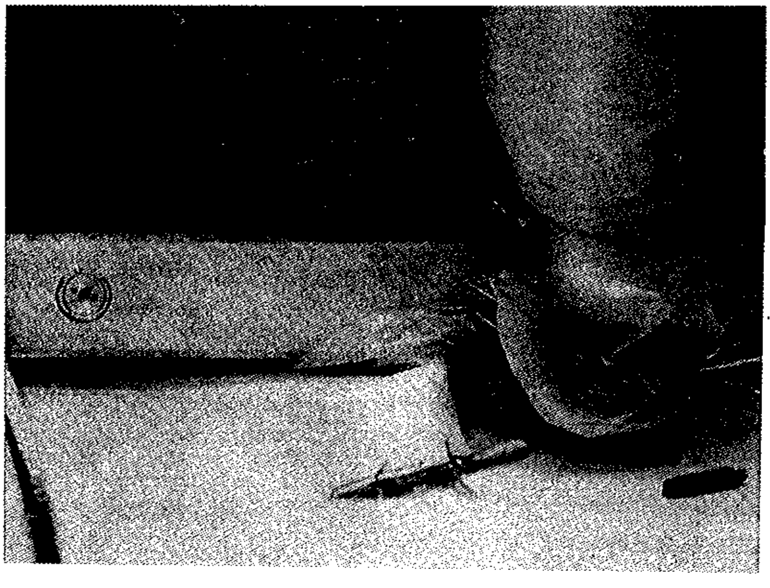


FIGURE 8 MADE–UP TELETHERAPY SOURCE IN THE "DRAWER" OF THE SHIELDED TRANSFER CONTAINER.

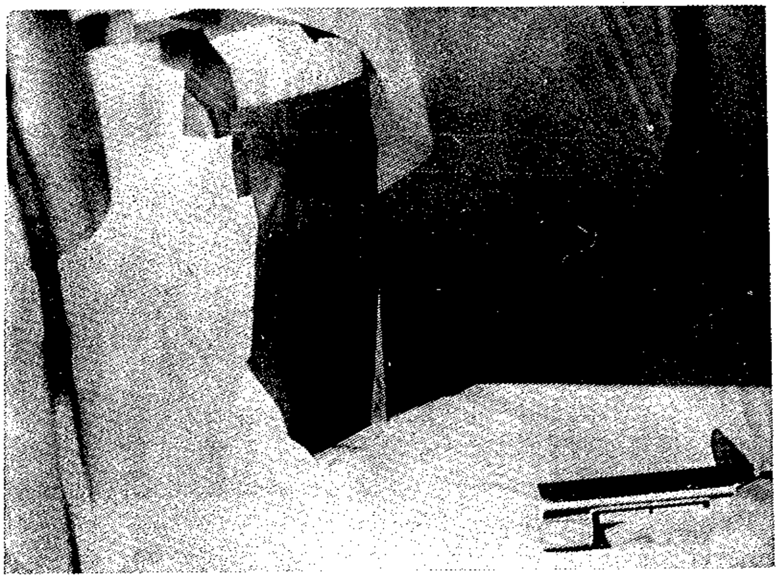


FIGURE 9 MADE-UP SOURCE AND DRAWER ARE PLACED INTO THE LOWER PART OF THE SHIELDED TRANSFER CONTAINER.
(Drawer seen in the upper part of the container is a shielding "dummy").

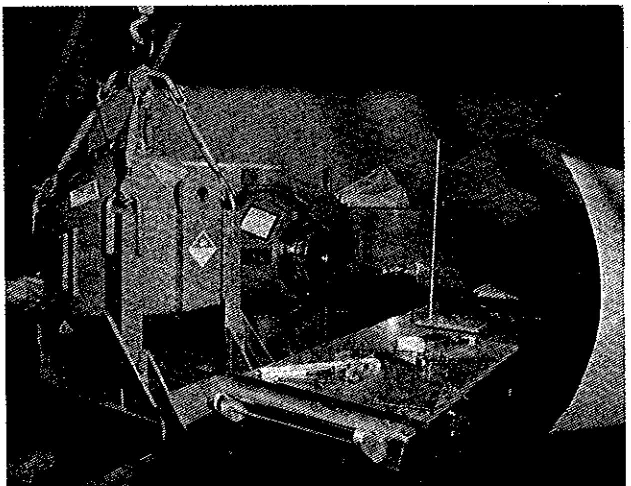


FIGURE 10 THE TRANSPORT CONTAINER IS ALIGNED TO THE TELETHERAPY HEAD PLACED AT 90 DEGREES TO ITS NORMAL OPERATIONAL POSITION.
(The shutter and collimator of the head can be seen pointing in the horizontal direction).

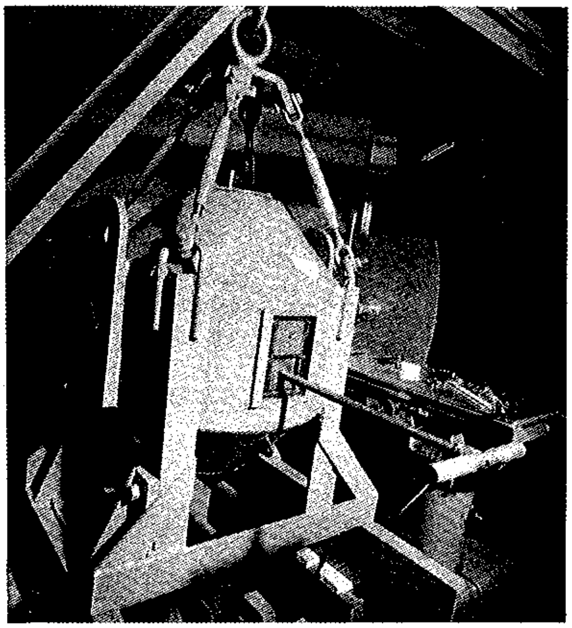
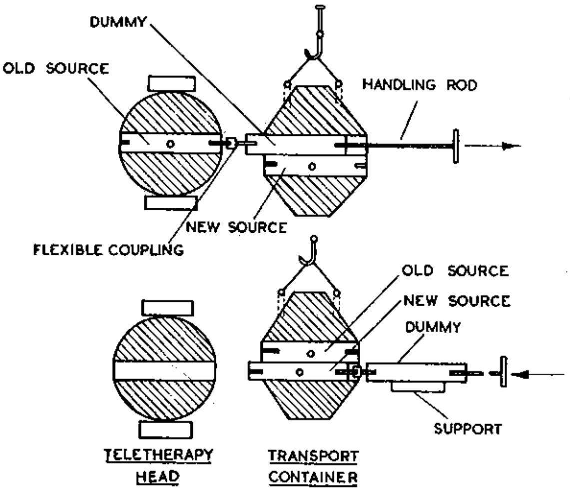


FIGURE 11 THE NEW SOURCE IS LOADED INTO THE TELETHERAPY UNIT.

Pull rod in the foreground is screwed into the "dummy" drawer which in turn is coupled to the drawer holding the new source. The head of the teletherapy unit is seen behind the transport container. The upper drawer in the transport container holds the old source.



A. WITHDRAWAL OF OLD SOURCE FROM TELETHERAPY HEAD INTO TRANSPORT CONTAINER.

B. CHARGING OF NEW SOURCE INTO TELETHERAPY HEAD.

FIGURE 12 METHOD OF SOURCE EXCHANGE

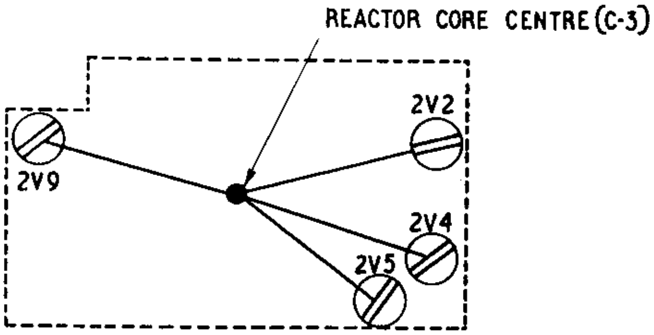


FIGURE 13 COBALT DISC ORIENTATION RELATIVE TO REACTOR CORE CENTRE