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AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
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THE AUSTRALIAN COMMONWEALTH STANDARD OF MEASUREMENT FOR ABSORBED RADIATION DOSE

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ABSTRACT

As an agent of the Commonwealth Scientific and Industrial Research Organization, the Australian Atomic Energy Commission (AAEC) is responsible for the maintenance of the Australian Commonwealth standard of absorbed dose. A graphite calorimeter was designed and built at the AAEC Research Establishment to provide such a standard for the dose absorbed in carbon from γ- and X-ray beams with maximum photon energies above 500 keV.

The calorimeter measures the dose averaged over the volume of a thermally insulated absorber disc of diameter 20 mm, thickness 3 mm and mass 1.7 g. The absorber and associated adiabatic and temperature controlled jackets are contained within a small graphite phantom of diameter 15 cm. The depth to the centre of the absorber is adjustable between 2.1 and 10 cm. By using a modified vacuum chamber window, the minimum depth can be reduced to 5 mm for use with high energy electron beams. The calorimeter has been in operation for more than 12 months and no change in its response to a ^{60}Co source has been detected in that time. The precision of dose measurements is ± 0.3 per cent at a dose rate of 4.2 mGy s^{-1} (25 rad min^{-1}).

Graphite and water phantoms have been made to enable portable working standards of absorbed dose in carbon and water to be calibrated against the primary standard.

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RADIATION DOSES; CALORIMETRIC DOSEMETERS; SPECIFICATIONS; PHANTOMS; CALIBRATION STANDARDS; GAMMA RADIATION; X RADIATION; GRAPHITE; WATER; AUSTRALIA;

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1. INTRODUCTION

In Australia, most national standards of measurement of physical quantities are maintained by the National Measurement Laboratory (NML), a division of the Commonwealth Scientific and Industrial Research Organization (CSIRO). In a small number of cases, where other scientific organizations have the specialized facilities and expertise required for standardizing a particular quantity and where there would be considerable cost to the NML in setting up similar facilities, the CSIRO has the power to authorize such organizations to act as its agents. In these cases, the agent has full responsibility and the same authority as the NML in performing the role of a national standard laboratory for that particular quantity. Absorbed radiation dose is one quantity for which this has occurred. The Australian Atomic Energy Commission (AAEC) is the authorized agent of the CSIRO for the maintenance of the Commonwealth standard of absorbed dose through the practical realization of the corresponding SI unit, the gray (Gy). This arrangement is not necessarily permanent but it is appropriate to the current situation.

The main purpose of this report is to describe an irradiation facility and instrumentation which have been developed at the AAEC Research Establishment for the maintenance of a primary standard of absorbed dose in carbon.

Calorimeters have been developed for primary dose standards in other national standards laboratories but little has been published about them. The US National Bureau of Standards (NBS) has built two calorimeters which operate in a heat loss compensation mode, first proposed by Domen [1969]. One of these calorimeters has been described in some detail by Domen & Lamperti [1974]. Brief descriptions of calorimeters developed at the UK National Physical Laboratory (NPL), the National Research Council of Canada and the Physikalisch-Technischen Bundesanstalt in West Germany have been published by the Bureau International des Poids et Mesures [BIPM 1975].

With the exception of the NPL instrument, all these calorimeters were constructed and operated in accordance with normal practice. Electrical heating elements were embedded in the absorber for calibration, and temperature changes in the absorber were registered by an embedded thermistor connected into one arm of a d.c. Wheatstone bridge. The NPL calorimeter is unusual in that the anisotropic property (high resistivity in one direction) of the pyrolytic graphite used for the absorber and jacket was used in a self-heating electrical calibration system. Another departure from usual practice was the use of a phase sensitive a.c. bridge in the temperature measuring circuit. This allowed a servo system to be used for the automatic calibration of the calorimeter during irradiation. A direct readout of the energy imparted to the absorber is another novel feature of this instrument. There does not appear to have been any publication on the performance of this calorimeter to date.

The Australian calorimeter was designed along conventional lines, but particular care was taken to obtain uniformity in the electrical heating pattern for the absorber-jacket system and to achieve good thermal isolation of the absorber. The design also achieved very small gaps (0.25 mm) between the absorber and jacket and between jackets.

Further reports will deal with the calibration of secondary standards of absorbed dose in carbon and water, and the effect on radiation quality of absorption and scattering in phantoms of various materials for various radiation sources.

All values of uncertainty quoted in this report correspond to one standard deviation.

2. IRRADIATION FACILITY

The gamma radiation source used by the radiation standards group at the AAEC Research Establishment is a 70 TBq (1.9 kCi) ^{60}Co source. It is housed in an Eldorado 6 teletherapy head unit made by Atomic Energy of Canada Ltd. A 50 TBq (1.4 kCi) ^{137}Cs source is also available for use in this machine.

The unit is installed in a shielded room approximately 4.9 x 4.2 m. A horizontal beam mode is normally used, but the head can be rotated (and elevated) to project a vertical beam if required. A fully adjustable rectangular aperture provides any field size in the range 5.8 cm square to 42 cm square at a distance of 1 m. A heavy optical bench mounted on a trolley (with floor guide rail) is used to position the primary standard and other dosimeters in the beam (Figure 1).

3. PRIMARY STANDARD

The quasi-adiabatic graphite calorimeter, developed to provide a primary standard of absorbed dose, was designed particularly for use with photon beams but provision has been made for the replacement of the thick graphite window in the vacuum chamber housing the calorimeter by a thin Melinex window. This will enable the calorimeter to be used for high energy electron beams.

3.1 Description

This calorimeter is an improved version of an earlier experimental aluminium calorimeter [Urquhart *et al.* 1973, 1974]. It measures the absorbed dose in carbon, averaged over the volume of a thermally insulated graphite absorber disc of diameter 20 mm, thickness 3 mm and mass ~ 1.7 g. This disc is suspended within an adiabatic graphite jacket with external dimensions 40 mm diameter x 6.5 mm (Figures 2 and 3). This jacket is contained within a temperature controlled jacket (Figures 4 and 3). The evacuated gaps between the absorber and jacket and between jackets are approximately 250 μm. The calorimeter is contained within a temperature controlled graphite phantom of diameter 15 cm (Figures 5 and 6) which is suspended inside an aluminium vacuum chamber (Figure 5). By attaching graphite plates to the front of the phantom, the depth to the centre of the absorber can be varied from 2.1 to 10 cm. The complete system is made from a single block of high density (1.8 g cm^{-3}) electrographite, type EY927. The graphite has a thermal conductivity of 130 to 150 W m^{-1} K^{-1} and an electrical resistivity of 1.2×10^{-7} to 1.4×10^{-7} Ω m. A block diagram of the primary standard assembly and the associated electronics is shown in Figure 7; this figure also refers to diagrams of the circuits of individual units.

Electrical heating elements are embedded in the absorber and the adiabatic jacket. The resistance wires are cemented into 127 μm wide spiral channels (Figures 2 and 3). The spirals each have the same pitch and are arranged in equally spaced planes to obtain a uniform heating pattern and to minimize temperature gradients across the absorber-jacket interface.

The calorimeter is calibrated by uniformly heating the absorber and jacket with a measured amount of electrical power applied for a measured time, and observing the corresponding change in the resistance of a microthermistor embedded in the absorber. No radiation energy is delivered to the calorimeter during calibration. A dose rate measurement can be made immediately after calibration by turning off the electrical heater power and exposing the calorimeter to the gamma-ray beam. A measurement of the irradiation time required to produce the same change in the thermistor resistance as produced by the electrical heating enables the dose rate to be computed directly.

Small corrections are required for the temperature drift of the absorber; this is measured before and after each electrical or radiation heating episode. The temperature controlled jacket is maintained at a constant temperature when there is no input of electrical or radiant energy to the absorber. While the absorber and adiabatic jacket are being heated, the temperature of the controlled jacket is made to follow that of the absorber by manually adjusting its control bridge. This enables a series of consecutive measurements to be made without disturbing the thermal equilibrium of the calorimeter. The room temperature is kept at 1 to 4 K below that of the phantom which is maintained at a constant temperature (see Figure 8).

The fine copper lead wires from the thermistors and heaters in the absorber pass through long circuitous channels in the surrounding jackets. The leads are cemented into these channels to obtain the good thermal contact needed to isolate the absorber from changes in ambient temperature.

A schematic circuit diagram of the calorimeter, showing the heaters and thermistors is given in Figure 8. The circuit used to supply the electrical power for calibration is shown in Figure 9. There are two heat control systems for the temperature controlled jacket. One is referred to in Figures 7 and 8 as a stand-by controller. This is a simple solid state circuit which runs continuously when the calorimeter is not in use and keeps it close to the operating temperature. When measurements are to be made, an alternative high sensitivity controller is switched in. This circuit includes a 'chopper' type null detector which is not suitable for continuous operation.

The response of the calorimeter to irradiation or electrical heating is measured by a d.c. bridge (Bridge No.5, Figure 7) in which one arm is formed by the absorber thermistor (T1 or T2). This bridge uses a second null detector. The detector output is at present recorded on a potentiometric recorder but this is to be supplemented later by a digital data acquisition system.

3.2 Performance

The practice has been adopted of making dose determinations by taking the mean of five successive dose measurements. Each measurement consists of five runs – drift, calibration (using electrical heating), second drift, a radiation run and third drift. A single determination (*i.e.* mean of five measurements) takes about 2.5 hours at a dose rate of 4.2 mGy s^{-1} (25 rad min^{-1}).

Under these conditions, dose determinations can be made with a precision of 0.3 per cent and the minimum dose rate at which measurements can be conveniently made is about 1 mGy s^{-1} (6 rad min^{-1}).

The same dose has been measured with thermistor T1 which is located near the edge of the absorber (Figure 2) and using the spare thermistor T2 at the centre. It was found that the measured dose was independent of the location of the thermistor. It seems unlikely that this result would have been obtained had thermal gradients in the absorber been a significant source of error.

Typical records of radiation heating of the calorimeter and of electrical calibrations are shown in Figures 15 and 16 respectively.

Calibrations of secondary and tertiary standard instruments will generally be made by observing their response under standard irradiation conditions for which the dose has been measured by the primary standard. Any small experimental discrepancies from these conditions will be corrected when computing the results, so all measurements (primary dose measurement or secondary standard response) will be the dose or response expected under the ideal standard conditions. The standard conditions are as follows:

(i) the measuring point (that is the centre of the calorimeter absorber or cavity of an ion chamber) is within, and on the central axis of, a graphite phantom having the same dimensions as the calorimeter phantom;

(ii) beam axis is normal to the front face of the phantom and passes through its centre;

(iii) distance from the source to the surface of the phantom (SSD) is 100.00 cm;

(iv) field size at 100 cm is 7.3 x 7.3 cm;

(v) depth (d_o) is 5.00 g cm^{-2}; and

(vi) phantom density is 1.800 g cm^{-3}.

The last two conditions imply a standard source to measurement point distance (z_o) of 100.0 + 5.0/1.8 = 102.78 cm. For the ^{60}Co source at present in use, all measurements are corrected for source decay to the time of installation of the source (6 November 1972) at a half-life of 1922 days.

The standard field size quoted in (iv) above is the optimum size for this calorimeter. A substantially smaller field could result in non-uniform heating of the absorber-jacket system and the required adiabatic heating conditions would not be achieved. A larger field size extending outside the phantom could produce extraneous radiation scattered from the aluminium vacuum chamber or other external bodies. The latter problem has been minimized by mounting the dummy calorimeter phantom (Section 4.1) in an aluminium housing having the same shape and dimensions as the calorimeter vacuum chamber. A secondary standard when being calibrated in the dummy phantom then 'sees' approximately the same extraneous radiation as the calorimeter. The setting of the aperture of the teletherapy machine for optimum field size is not critical from the point of view of the calorimeter performance. It is, however, necessary to reproduce accurately any field size used for a calibration since dose rate is a slowly varying function of the beam dimensions. For example, it is necessary to be able to reproduce the standard field height and width (7.3 cm) to an accuracy of ± 0.5 mm. Since this is quite easy to achieve, field settings are not a significant source of error in dose calibrations.

3.2.1 Long-term stability

The long-term stability of the calorimeter was tested by making repeated measurements of dose (D_o) under standard conditions over a period of 12 months. The results obtained are listed in Table 1.

It can be seen from the table that the standard deviation for the set of 11 determinations made over a 12 month period (i.e. 0.023) is in agreement with the value $0.07/\sqrt{5} = 0.03 \pm 0.1$ predicted from the mean of the standard deviations (0.07) of the sets of five measurements made on one day. That is, the long-term variation in dose determinations is no greater than the short-term statistical fluctuations observed in the course of a day's measurements.

A linear least-squares fit was also made to the dose/time distribution and the slope was found to be 0.1 ± 0.3 per cent per year; that is, there was no detectable drift in the calorimeter during this period.

3.2.2 Comparison with aluminium calorimeter

There has been no opportunity to compare the primary standard with those in other laboratories, but a comparison has been made with the aluminium calorimeter referred to in Section 3.1. The comparison was made by means of an NPL designed thimble ionization chamber (Section 5). This chamber was fitted with a graphite build-up cap and placed in a dummy graphite calorimeter phantom (Section 4.1). Its response (I_c) was measured under the standard irradiation conditions and a 'dose in carbon' calibration factor $N_c = \dot{D}_o/I_c$ obtained.

This chamber (with its graphite build-up cap) was then placed in a dummy aluminium calorimeter phantom and its response $I_{A\ell}$ measured under irradiation conditions for which the dose rate in aluminium ($\dot{D}_{A\ell}$) had been found previously by the aluminium calorimeter. The dose rate in carbon (in the aluminium phantom) is given by:

$$\dot{D}_c = I_{A\ell} . N_c \quad ; \tag{1}$$

from this the dose rate in aluminium ($\dot{D}_{A\ell}$) can be computed from the equation:

$$\dot{D}_{A\ell} = \dot{D}_c . F \left(\frac{\bar{\mu}_{en}}{\rho}\right)_{A\ell} \bigg/ \left(\frac{\bar{\mu}_{en}}{\rho}\right)_c \quad , \tag{2}$$

where F = a displacement factor which corrects for the change in fluence at the point of measurement, produced by replacing the ion chamber and build-up cap by aluminium (rather than graphite), and

$\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{material}$ = the mean mass energy absorption coefficient averaged over the photon energy spectrum at the point of measurement.

The displacement factor was estimated experimentally by measuring the dose attenuation over a distance equal to the build-up cap radius (0.828 cm) in aluminium and graphite. The source to measurement point distance was kept constant during these measurements to simulate parallel beam conditions. The attenuation was 0.9296 in aluminium and 0.9449 in graphite so F = 0.9838.

The photon spectra in the aluminium and graphite phantoms and the mean absorption coefficients were calculated by a Monte Carlo computer program to be described elsewhere. The values obtained for the coefficients were:

$$\left(\frac{\bar{\mu}_{en}}{\rho}\right)_c = 0.0271 \text{ cm}^2 \text{ g}^{-1}, \quad \text{and}$$

$$\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{A\ell} = 0.0269 \text{ cm}^2 \text{ g}^{-1} \quad ,$$

so that

$$\dot{D}_{A\ell}/\dot{D}_c = 0.9765 .$$

The dose rate in aluminium found in this way was 1.1 per cent lower than was obtained directly by the aluminium calorimeter. The systematic uncertainty in this comparison is hard to estimate but it is unlikely to exceed ± 3 per cent.

3.3 Correction Factors

3.3.1 Impurity materials

Impurities in the calorimeter can affect the measured dose in two ways. Firstly, the impurities in the absorber (Table 2) have energy absorption coefficients that are different from that of carbon and cause anomalous energy absorption. Secondly, impurities throughout the complete calorimeter change the photon fluence at the centre of the absorber.

The first effect can be evaluated in terms of an effective absorber mass m_o, defined by

$$D_o = \Delta E/m_o \quad , \tag{3}$$

where ΔE = the measured energy absorbed by the actual calorimeter absorber when exposed to a photon energy fluence ϕ_o, and

D_o = the absorbed dose in an ideal absorber, with no impurities, when the same energy ΔE is absorbed from the same fluence ϕ_o.

From this definition it follows that

$$\Delta E = \phi_o \left(\frac{\bar{\mu}_{en}}{\rho}\right)_c m_o = \phi_o \left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_c m_c + \sum_{i=1}^{i=n} \left(\frac{\bar{\mu}_{en}}{\rho}\right)_i m_i\right] \quad , \tag{4}$$

where m_c = the mass of carbon in the absorber,

m_i = the mass of the i^{th} impurity element,

$\left(\frac{\bar{\mu}_{en}}{\rho}\right)_c$ = the mean mass energy absorption coefficient for carbon, and

$\left(\frac{\bar{\mu}_{en}}{\rho}\right)_i$ = the mean coefficient for the i^{th} impurity element, both averaged over the spectrum of photon energies at the point of measurement. Therefore

$$m_o = m_c + \sum_{i=1}^{i=n} \left(\bar{\mu}_{en}/\rho\right)_i \Big/ \left(\bar{\mu}_{en}/\rho\right)_c \, m_i \quad . \tag{5}$$

The second effect can be evaluated approximately by considering the impurity materials (density ρ_j) to be in the form of shells of thickness

Δd_j surrounding the centre of the absorber.

Let x_a = the actual photon energy fluence at the centre of the absorber, and x_o = the fluence at the centre of an ideal calorimeter in which the impurity materials have been replaced by graphite.

Then

$$\frac{x_o}{x_a} \approx \exp\left[\sum_{j=1}^{j=n} \Delta d_j \quad (\bar{\mu}_j - \bar{\mu}_c)\right] \quad , \tag{6}$$

where $\bar{\mu}_j$ = the mean attenuation coefficient for the j^{th} impurity material, and

$\bar{\mu}_c$ = the mean attenuation coefficient for graphite.

The correction factor k_i for the total effect of impurities can now be calculated. If k_i is defined by

$$D_o = k_i . D_a$$

where D_a = the dose measured by the actual calorimeter, and

D_o = the dose measured by an ideal calorimeter free of impurities, then

$$k_i = \frac{m_a}{m_o} \cdot \frac{x_o}{x_a} \quad , \tag{7}$$

where m_a = the mass of the actual absorber.

Values of the parameters required to calculate k_i at various depths in the calorimeter phantom for the ^{60}Co teletherapy source are shown in Tables 3 and 4 and computed values of k_i are shown in Table 4.

Under standard irradiation conditions,

$$k_i = 0.9981 \pm 0.0005.$$

3.3.2 Attenuation in the absorber

The calorimeter measures the dose $\bar{D}_a$ averaged over the volume element occupied by the absorber. The dose D_o required is that at the centre of the absorber. A correction factor k_a can be defined such that

$$D_o = k_a \bar{D}_a .$$

The dose (D_d/D_s) at any depth d, relative to the dose at an arbitrary reference depth d_s in the calorimeter phantom (along the beam axis), can be expressed by a polynomial equation:

$$D_d/D_s = f(d) = A_0+A_1d+A_2d^2+A_3d^3+A_4d^4 \tag{8}$$

where the coefficients A_0, A_1 etc can be found by least-squares fitting the equation to a set of depth dose measurements.

If the radiation field at any depth in the absorber is uniform in a radial direction (i.e. normal to beam axis), then the mean dose $\bar{D}_a$ is given by:

$$\bar{D}_a/D_s = \frac{\int_{d_1}^{d_2} f(d)\, dd}{d_2-d_1} = \frac{\emptyset(d_2)-\emptyset(d_1)}{d_2-d_1} , \qquad (9)$$

where $\emptyset(d) = A_o d + \frac{A_1}{2} d^2 + \frac{A_2}{3} d^3 + \frac{A_3}{4} d^4$ (10)

and d_1 and d_2 are the depths to the front and rear faces of the absorber. The 4th order polynomial was chosen because a reduced chi square test [Bevington 1969] showed it to be a good fit to the experimental depth dose data.

Since

$$D_o/D_s = f(d_o) \quad ,$$

where d_o = the depth to the centre of the absorber,

$$k_a = \frac{f(d_o)\,(d_2-d_1)}{\emptyset(d_2)-\emptyset(d_1)} \quad . \qquad (11)$$

The values obtained for the coefficients of equation (8) for standard irradiation conditions and for a reference depth $d_s = 5.0$ g cm^{-2} were:

$A_0 = 1.2443$ $A_1 = -5.4380 \times 10^{-2}$

$A_2 = 1.3770 \times 10^{-3}$ $A_3 = -6.2216 \times 10^{-5}$

$A_4 = 1.5343 \times 10^{-6}$

and therefore

$$k_a = 1.00095 \pm 0.00005.$$

3.3.3 Depth correction

A correction factor k_d can be defined so that

$$D_o = k_d . D_d \ ,$$

where D_o = the dose at the ideal standard depth $d_o = 5.000$ g cm^{-2} and

D_d = the dose at the actual depth d of the centre of the calorimeter absorber when it is operating under nominally standard conditions, and $(d_o-d) \ll d_o$.

From equation (8),

$$k_d = f(d_o)/f(d).$$

The value of d for the calorimeter = 4.9655 g cm^{-2}, so

$k_d = 0.9985 \pm 0.0005.$

3.3.4 Distance correction

The bulk density of the calorimeter differs from the reference value of 1.80 g cm^{-3}. The average density of the graphite itself differs slightly from this value and vacuum gaps and impurity materials cause further discrepancies. Consequently at the standard SSD (100 cm) and standard depth (5.0 g cm^{-2}), the source to measurement point distance (z_o) differs from the reference value (102.78 cm). To avoid the necessity for a distance correction, the SSD for the calorimeter is changed to 99.83 cm so that z_o is, in fact, 102.78 cm and the depth correction factor $k_z = 1.0 \pm 0.0005$.

3.3.5 Calibration correction

The electrical energy ΔE_c delivered by the calibrator can be measured accurately but the energy ΔE_o received by the calorimeter absorber is reduced by heat losses in the leads between the absorber and the calibrator. A correction factor k_c can be defined such that:

$$\Delta E_o = k_c \, \Delta E_c \quad .$$

Since $\Delta E_c = \Delta t \; I_c^2(R_\ell+R_h)$, and $\Delta E_o = \Delta t \; I_c^2 \, R_h$,

where Δt = the calibration heating time,

I_c = the calibration current,

R_h = the resistance of the absorber heater, and

R_ℓ = the resistance of the leads,

we have $k_c = R_h/(R_\ell+R_h)$.

Here $R_h = 776.6\ \Omega$, $R_\ell = 3.815\ \Omega$ and $k_c = 0.9951 \pm 0.0005$.

3.4 Absolute Accuracy

As with most primary standards of physical quantities, it is not possible to make a meaningful statement about the absolute accuracy of this standard. One fundamental source of uncertainty is the possibility of a heat defect in graphite associated with radiochemical changes in the absorbed oxygen. Bewley & Page [1972] have reported a heat defect of 2 ± 2 per cent but Sabël *et al.* [1973] and Domen & Lamperti [1976] were not able to detect any evidence of this.

Since most users of a measurement service are interested in relative rather than absolute values, a small discrepancy between the 'as maintained' unit and the SI unit is not of great practical importance. A 'maintained unit' of adequate long-term stability and precision can provide the essential assurance of uniform measurement on the national scale and, internationally through international comparisons of primary standards. The policy of the CSIRO [1977] is to disregard any possible systematic errors in its 'as maintained' units when making statements of uncertainty.

4. PHANTOMS

Since the calorimeter is not easily portable, the standard is most readily disseminated by means of secondary or working standards which can be calibrated against the primary standard. To facilitate these calibrations three phantoms have been made.

4.1 Dummy Calorimeter Phantom

This is a graphite phantom made to the same dimensions as the calorimeter phantom and housed in an aluminium structure which simulates the calorimeter vacuum chamber. This phantom has been designed to accommodate ionization chambers, chemical dosimeters and solid state dosimeters, so that they can be irradiated under the same conditions as the calorimeter absorber. These dosimeters can therefore be calibrated, in terms of absorbed dose in carbon, by direct comparison with the primary standard.

4.2 The BIPM Graphite Phantom

A second graphite phantom was constructed to enable subsidiary dose standards to be calibrated against the working standards. This phantom is larger than the calorimeter phantom and provides greater freedom in the choice of field size and depth. It was modelled on the standard phantom used by the Bureau International des Poids et Mesures [BIPM 1973] and consists of an assembly of graphite discs 30 cm diameter and 28 mm thick. Eight discs can be accommodated in the metal framework which holds the graphite assembly.

4.3 Water Phantom

Since water is the medium preferred by the International Commission on Radiation Units and Measurements for standard dose measurements [ICRU 1969], it is also necessary to calibrate the secondary standards in terms of absorbed dose in water. A rectangular phantom 30 x 30 x 30 cm was constructed for this purpose.

5. WORKING STANDARDS

A thimble ionization chamber was chosen as the most suitable instrument for use as a secondary or working standard of absorbed dose. Instruments of this type are easily portable, can be made to have good long-term stability, and are quick and easy to operate.

For this purpose, an exposure meter designed at NPL and made by Nuclear Enterprises Limited (UK) was purchased. It consists of a type NE2560 measuring assembly (current integrator) and a type NE2561 graphite walled thimble chamber. A spare thimble chamber was also purchased.

5.1 Working Standard of Absorbed Dose in Carbon

The Delrin build-up cap supplied with the NE2561 chamber was replaced by a graphite one and the chamber was calibrated in the dummy calorimeter phantom under standard conditions (see Section 3.2). When calibrated, the dial reading of the NE2560 current integrator is simply multiplied by a calibration factor N_c to obtain the 'absorbed dose in carbon' directly. The chamber with its graphite build-up cap can then be used to measure the absorbed dose in carbon in any other gamma-ray field provided that allowance is made for differences in the quality of the field from that used for the calibration of the chamber. The changes in radiation quality which occur with increasing depth in a phantom have been investigated (for several radiation sources) by means of a Monte Carlo computer model. This model will be described in a later report.

5.2 Working Standard of Absorbed Dose in Water

Although water is the preferred medium for the standardization of absorbed dose, graphite was chosen for the primary standard because of the difficulties of designing a water calorimeter of sufficient accuracy. A working or secondary standard of absorbed dose in water is therefore needed. For this purpose, it was decided to use the same NE2560/2561 ion chamber system with the normal Delrin build-up cap. The primary dose in the graphite standard was transferred to a point in the water phantom by an experimental method. A calibration factor N_w for the secondary standard was then found by measuring its response at the transfer point in the water phantom.

The calibration of both working standards will be described more fully in a later report.

6. CONCLUSIONS

The calorimeter described has been shown to have the precision and long-term stability required for a primary standard of absorbed dose in carbon for ^{60}Co γ-radiation. Further work is expected to show that this standard can be readily disseminated by means of a simple portable working standard which can be calibrated against the calorimeter. It is also expected that further work will show that this standard can be used over a wide range of gamma energies, from 500 keV to at least 20 MeV and that, with slight modification, it can be used with high energy electron beams.

7. ACKNOWLEDGEMENT

The work of the AAEC Manufacturing Section in making the parts for the calorimeter is greatly appreciated. The machining of the small graphite parts in particular required considerable care and skill.

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TABLE 1

LONG-TERM STABILITY OF THE PRIMARY DOSE STANDARD

No.	Date	Dose rate determination $\dot{D}_o$* (mean of five measurements) (mGy s^{-1})	σ
1	2.2.76	7.604	0.064
2	9.2.76	7.574	0.088
3	13.2.76	7.635	0.054
4	17.3.76	7.576	0.069
5	15.4.76	7.584	0.046
6	20.5.76	7.631	0.103
7	11.6.76	7.614	0.089
8	26.7.76	7.584	0.027
9	8.10.76	7.631	0.052
10	26.11.76	7.585	0.106
11	8.2.77	7.608	0.091
Mean		7.602	0.072
σ		0.023	0.026

* ^{60}Co source at 6.11.72

TABLE 2

MATERIALS AND ELEMENTS USED IN THE
CONSTRUCTION OF THE CALORIMETER ABSORBER

Material	Composition	Mass (mg)	Element	Mass (mg)
Graphite	C	1674.95	C	1681.23
Aluminium	Al	0.98	H	0.74
Delrin	0.61 C +0.12 H +0.27 O	1.05	O	2.46
Karma Wire	0.8 Ni +0.2 Cr	9.01	Al	0.98
Thermistors	0.78 Fe +0.22 O ?	0.24	Cr	1.80
Platinum Wire	Pt	0.03	Fe	0.19
Copper Wire	Cu	1.71	Ni	7.21
Solder	0.3 Pb +0.7 Sn	0.04	Cu	1.71
Epoxy	0.71 C +0.07 H +0.22 O	5.56	Sn	0.03
Acrylic	0.60 C +0.08 H +0.32 O	2.68	Pt	0.03
Shellac	0.6 C +0.1 H +0.3 O	0.13	Pb	0.01
	Total Mass	1696.39		1696.39

TABLE 3

MEAN ABSORPTION COEFFICIENT $(\bar{\mu}_{en}/\rho)_i$ OF THE ABSORBER IMPURITIES AND THE EFFECTIVE ABSORBER MASS m_o FOR A ^{60}Co SOURCE

Component			$(\bar{\mu}_{en}/\rho)_i$ (cm^2 g^{-1}) at depth :			
i	Element	Mass m_i (mg)	5 g cm^{-2}	7 g cm^{-2}	10 g cm^{-2}	20 g cm^{-2}
c	C	1681.23	0.0271	0.0271	0.0272	0.0272
1	H	0.74	0.0539	0.0539	0.0540	0.0541
2	O	2.46	0.0272	0.0272	0.0273	0.0273
3	Al	0.98	0.0268	0.0269	0.0270	0.0271
4	Cr	1.80	0.0296	0.0302	0.0310	0.0316
5	Fe	0.19	0.0318	0.0328	0.0335	0.0345
6	Ni	7.21	0.0343	0.0350	0.0365	0.0377
7	Cu	1.71	0.0338	0.0345	0.0365	0.0374
8	Sn	0.03	0.05270	0.05451	0.05704	0.06021
9	Pt	0.03	0.1541	0.1530	0.1552	0.1620
10	Pb	0.01	0.0908	0.0938	0.0975	0.1011
Total mass, m_a = 1696.39						
∴ m_o (mg) =			1699.8	1700.1	1700.7	1701.1

where

$$m_o = m_c + \sum_{i=1}^{i=10} \left\{ \frac{(\bar{\mu}_{en}/\rho)_i}{(\bar{\mu}_{en}/\rho)_c} m_i \right\}$$

TABLE 4

MEAN MASS ATTENUATION COEFFICIENTS $(\bar{\mu}/\rho)_j$ FOR THE CALORIMETER IMPURITY MATERIALS, THE FLUENCE RATIO x_o/x_a AND THE CORRECTION FACTOR k_i

Component				$(\bar{\mu}/\rho)_j$ (cm^2 g^{-1}) at depth :			
j	Material	$(\Delta d_j . \rho_j)$ (mg cm^{-2})	ρ_j (g cm^{-3})	5 g cm^{-2}	7 g cm^{-2}	10 g cm^{-2}	20 g cm^{-2}
c	Graphite	-	1.80	0.0646	0.0647	0.0647	0.0652
1	Aluminium	1.1	2.70	0.0632	0.0633	0.0637	0.0640
2	Heater Wires	2.9	8.1	0.0707	0.0708	0.0739	0.0746
3	Bonding Material	1.8	1.15	0.0710	0.0711	0.0712	0.0717
4	Insulating Material	1.0	1.19	0.0710	0.0711	0.0712	0.0717
$\frac{x_o}{x_a} = \exp\left\{\sum_{j=1}^{j=4} \Delta d_j \ (\bar{\mu}_j - \bar{\mu}_c)\right\} =$				1.000105	1.000105	1.000114	1.000115
From Table 3 : $m_a/m_o =$				0.99798	0.99781	0.99745	0.99722
$\therefore \underline{k_i} =$				<u>0.9981</u>	<u>0.9979</u>	<u>0.9976</u>	<u>0.9973</u>
where $k_i = \frac{m_a}{m_o} \cdot \frac{x_o}{x_a}$							

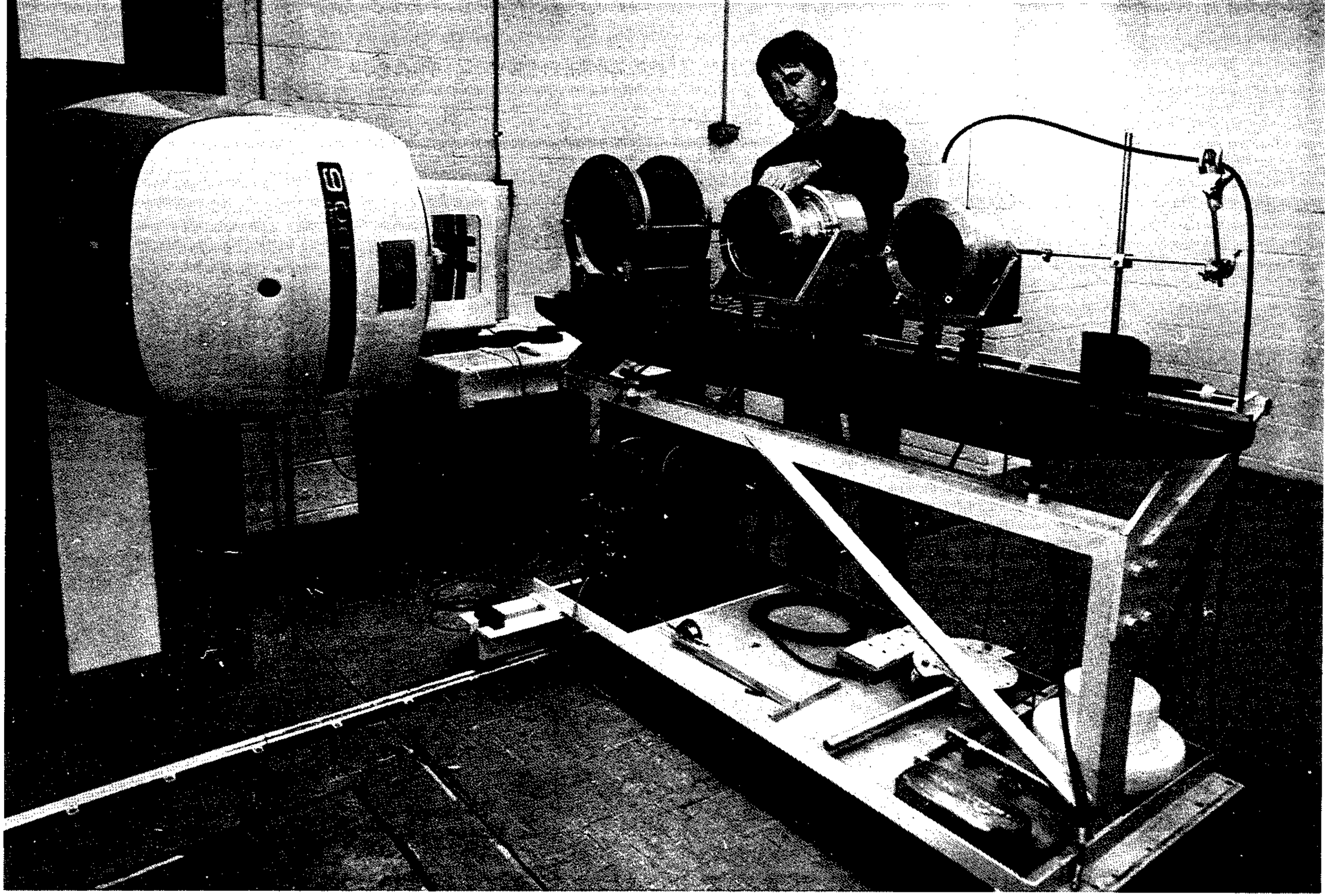


FIGURE 1. THE IRRADIATION CELL. THE PRIMARY STANDARD IS SHOWN BETWEEN THE DUMMY CALORIMETER PHANTOM AND THE LARGER BIPM PHANTOM

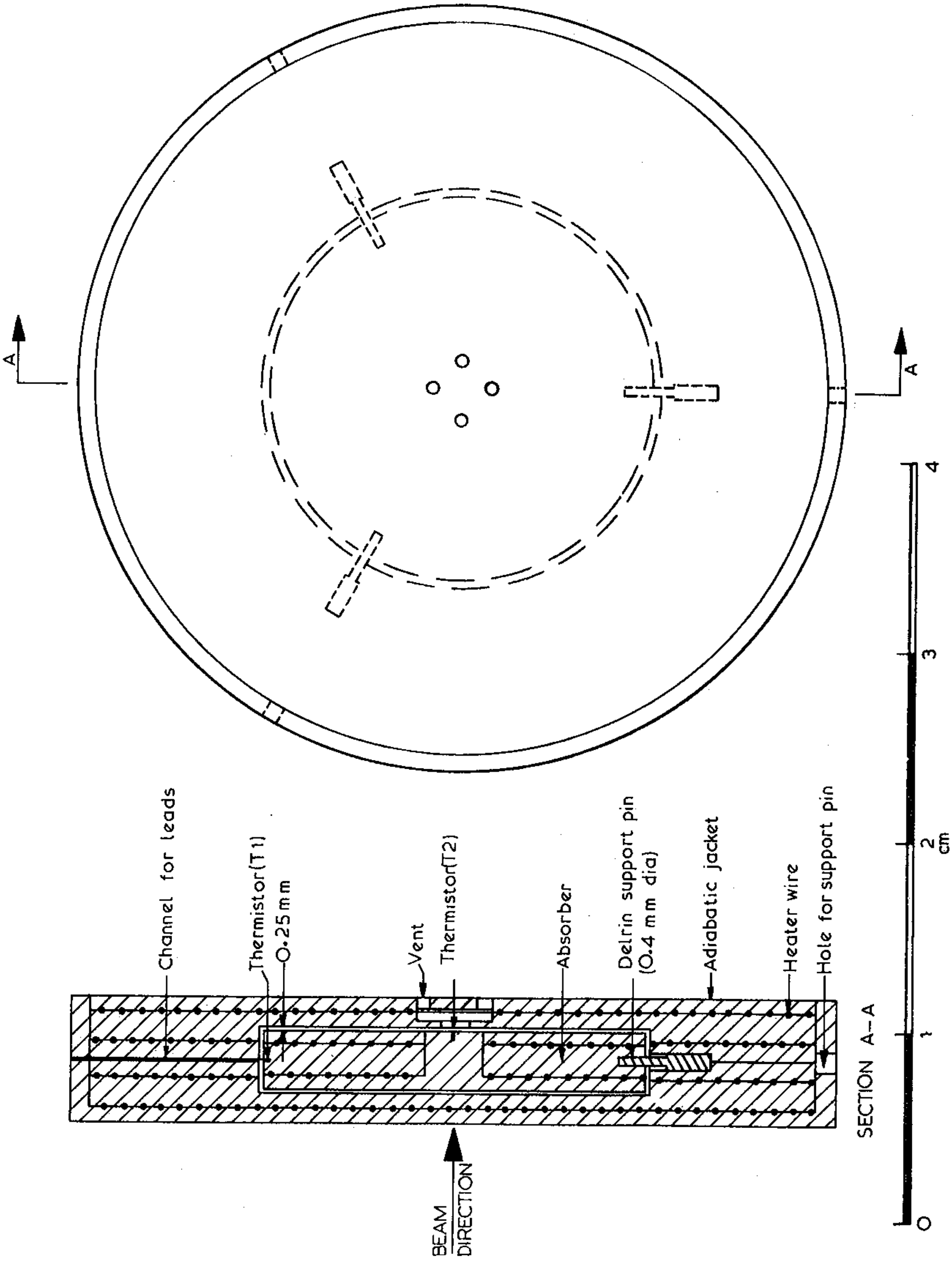


FIGURE 2. ABSORBER AND ADIABATIC JACKET

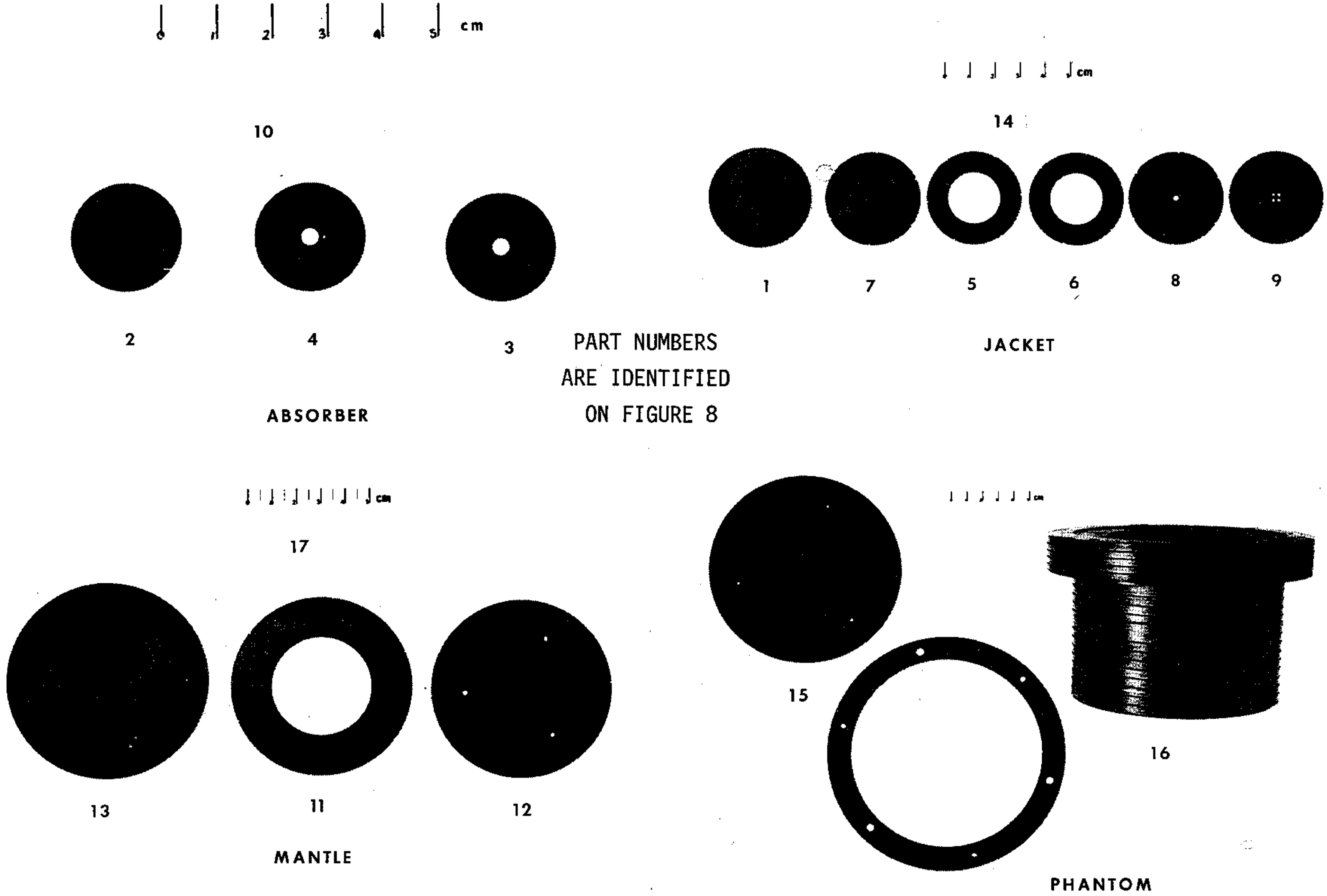


FIGURE 3. THE COMPONENTS OF THE ABSORBER, ADIABATIC JACKET, JACKET NO. 2 (MANTLE) AND PHANTOM

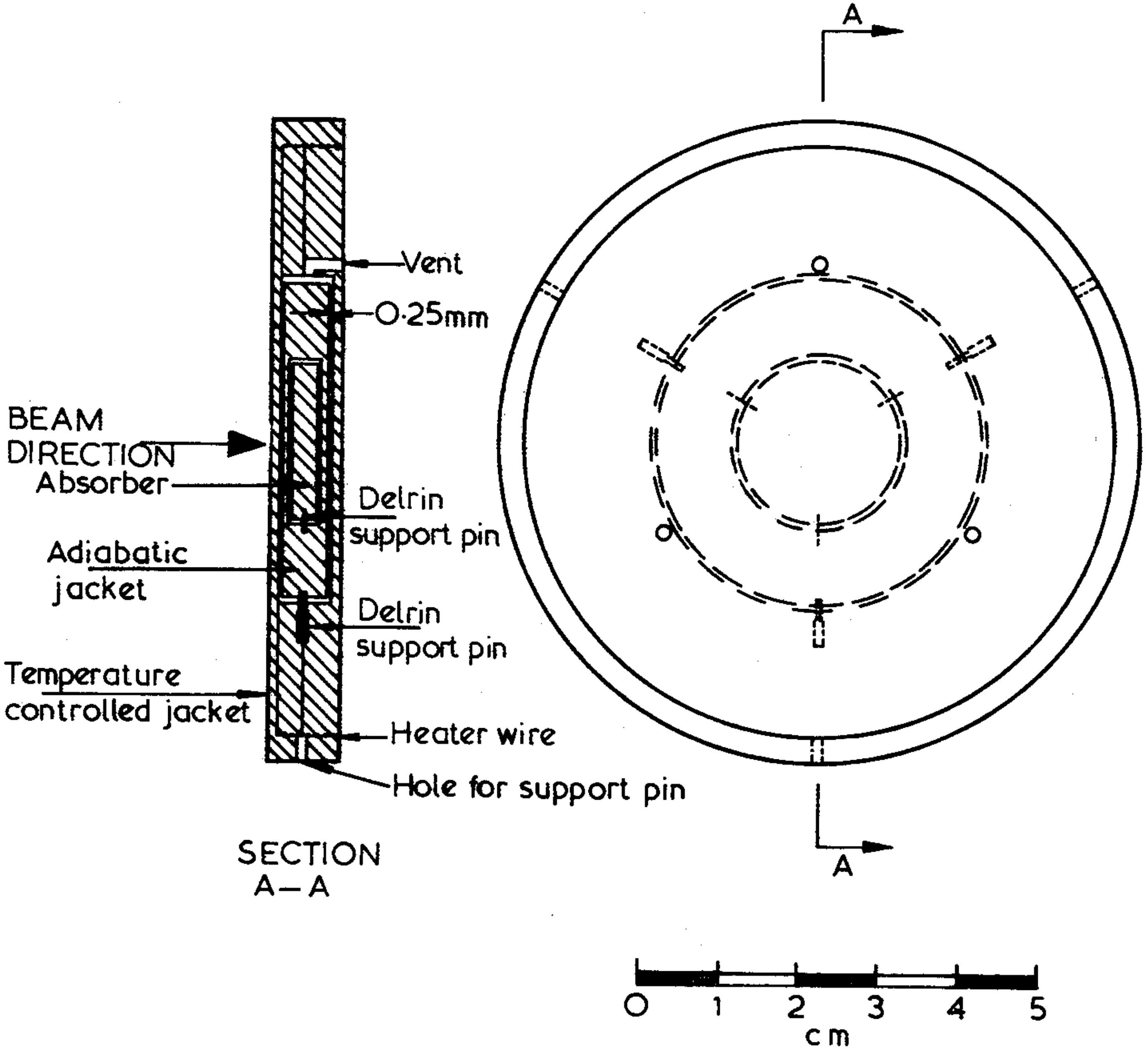


FIGURE 4. THE GRAPHITE CALORIMETER

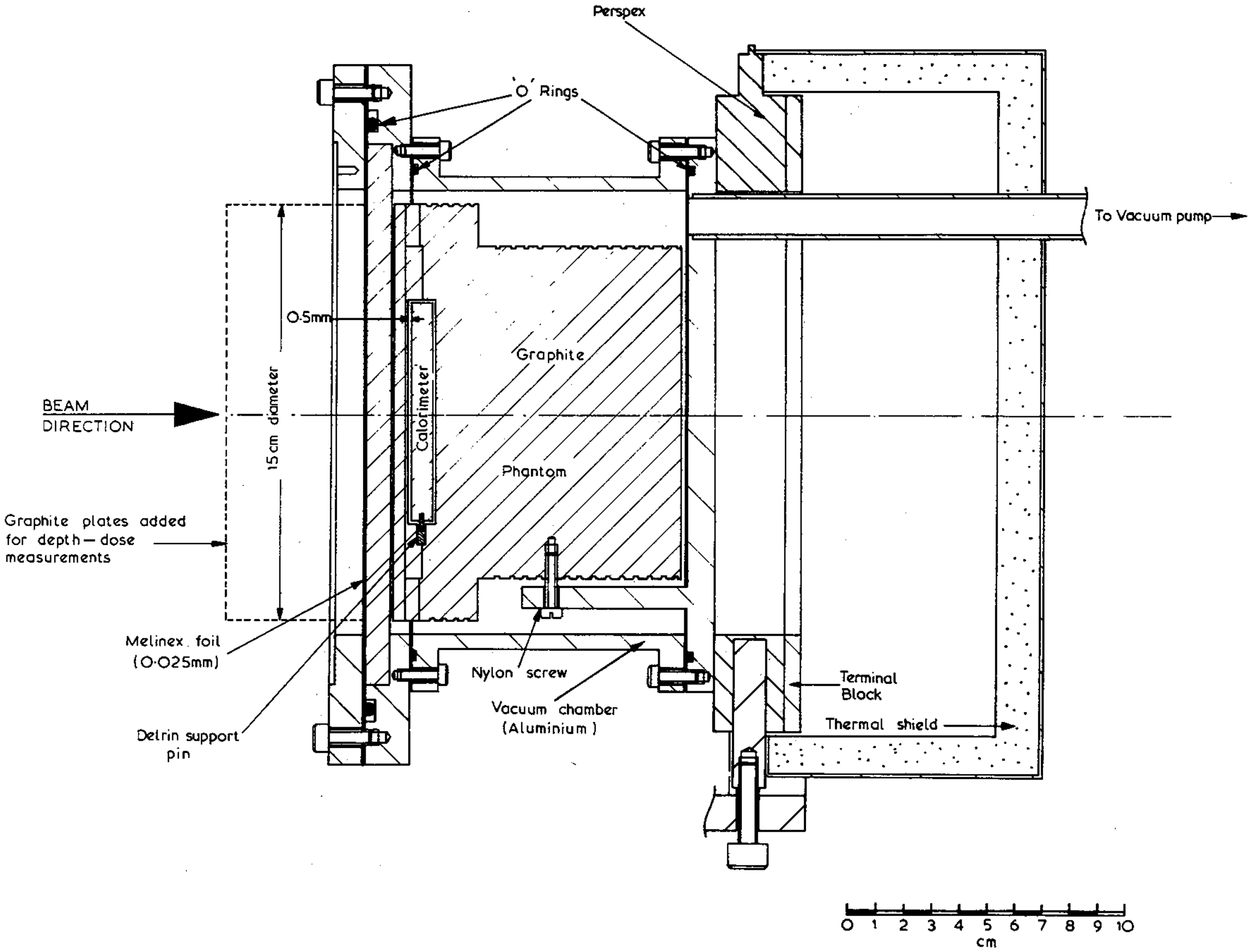


FIGURE 5. THE PRIMARY STANDARD OF ABSORBED DOSE IN CARBON

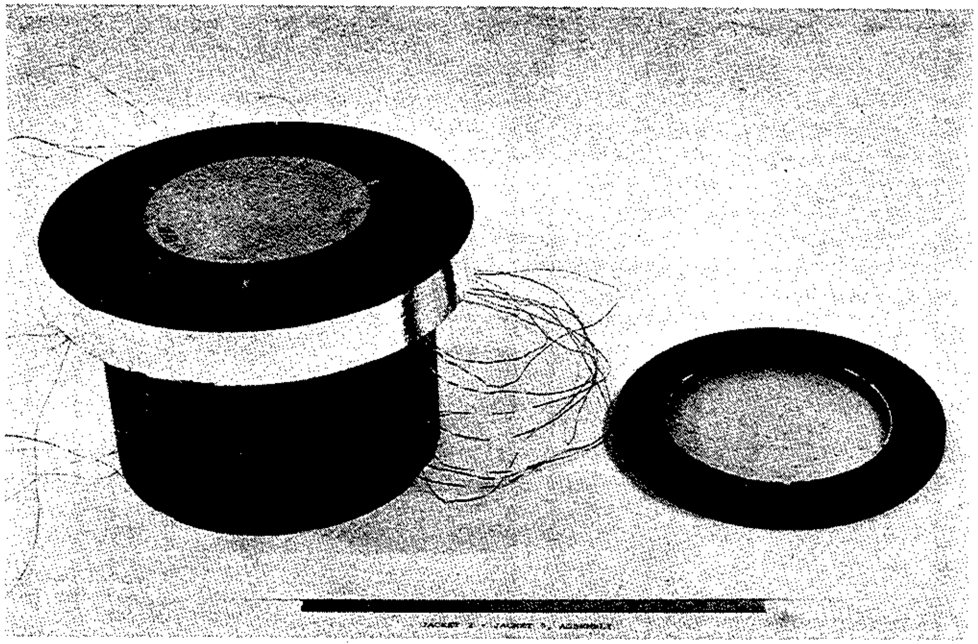


FIGURE 6. THE CALORIMETER (ALUMINIZED) IS SHOWN IN THE GRAPHITE PHANTOM (JACKET 3) DURING ASSEMBLY. THE TOP CAP OF THE PHANTOM IS SHOWN AT THE RIGHT

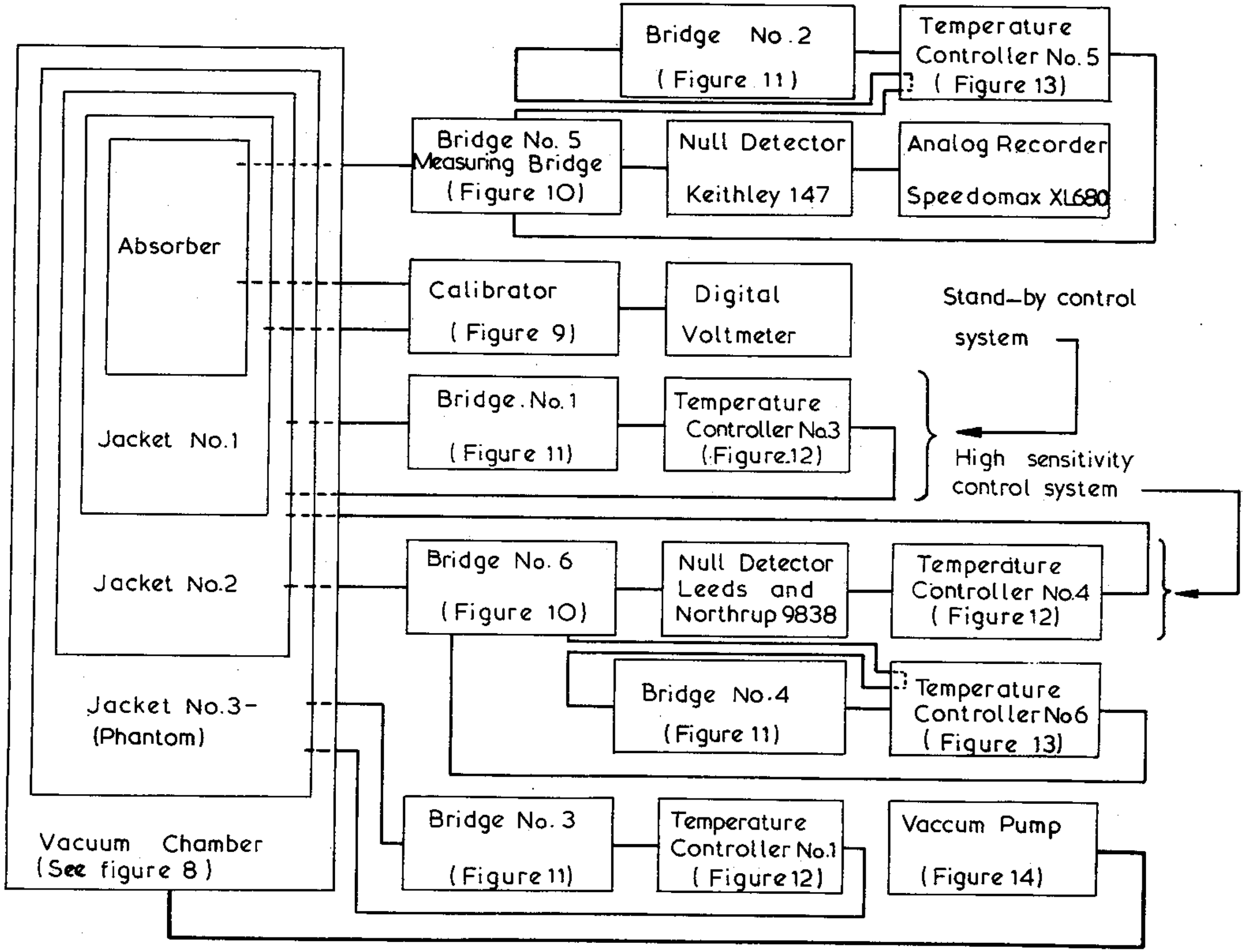


FIGURE 7. A BLOCK DIAGRAM OF THE COMPLETE CALORIMETER SYSTEM

THERMISTORS

Circuit Reference No	Location	Manufacturer and type No.	α At 28°C (%/°C)	Resistance at 28°C (Ω)
T 1	Absorber (Part No 4)	Veco, 33A78(1)	3·31	2315
T 2	Absorber (Part No 2)	Veco, 33A78(2)	3·31	2398
T 3	Jacket 1 (Part No 8)	Philips 232263412 222	Not Used	
T 4	Jacket 2 (Part No 12)	Veco, 33A82(1)	3·8	2110
T 5	•	Veco, 33A82(2)	3·8	2223
T 6	•	Philips,(1) 232263412 104	4·4	93600
T 7	•	Philips,(2) 232263412 104	4·4	90800
T 8	Jacket 3 (Part No 16)	Philips,(3) 232263412 104	4·4	94480 (27·5°C)
T 9	•	Philips,(4) 232263412 104	4·4	94280 (27·5°C)

HEATERS

Circuit Reference No.	Location	Wire		Resistance (Ω)	
		Type	Diameter (μm)	Part	Total
R 1	Absorber (Part No. 4)	Karma (Epoxy Enamel)	41	776·6	
R 2	Jacket 1 (Part No 7)	"	"	1778	6186
R 3	Jacket 1 (Part No.5)	"	"	1310	
R 4	Jacket 1 (Part No·6)	"	"	1329	
R 5	Jacket 1 (Part No8)	"	"	1769	
R 6	Jacket 2 (Part No 11)	Manganin (Enamelled)	120	54·2	108·4
R 7	Jacket 2 (Part No.12)	"	"	54·2	
R 8	Jacket 3 (Part No.16)	"	"	114	
R 9	Jacket 2	"	"	86·9	

LEADS AND TERMINALS

Numbers on leads show wire diameters (μm)

All leads from absorber and jackets are in close thermal coupling with surrounding jackets.

The terminals drawn in heavy lines are low thermal type in good thermal contact with a common heat sink

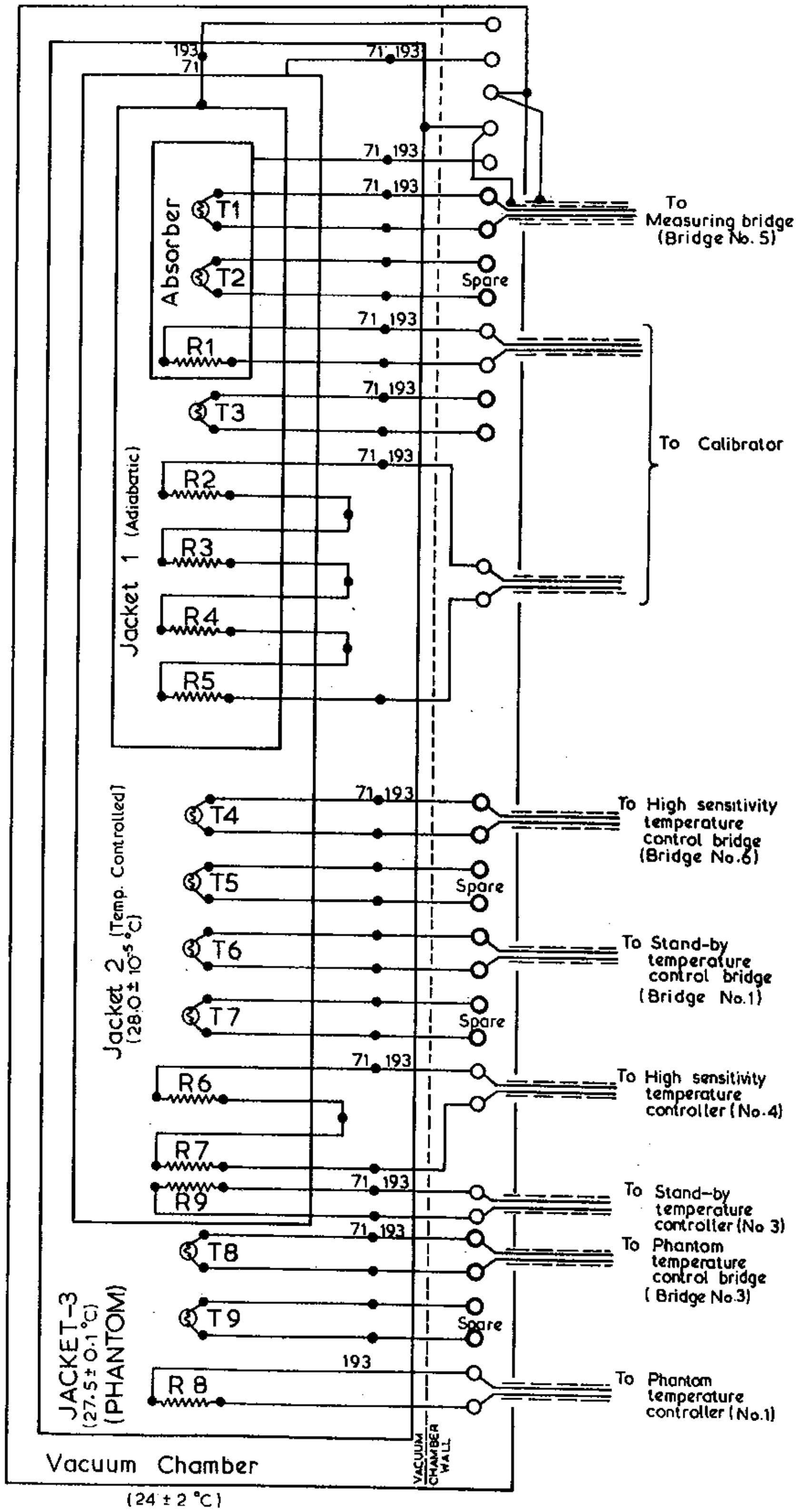
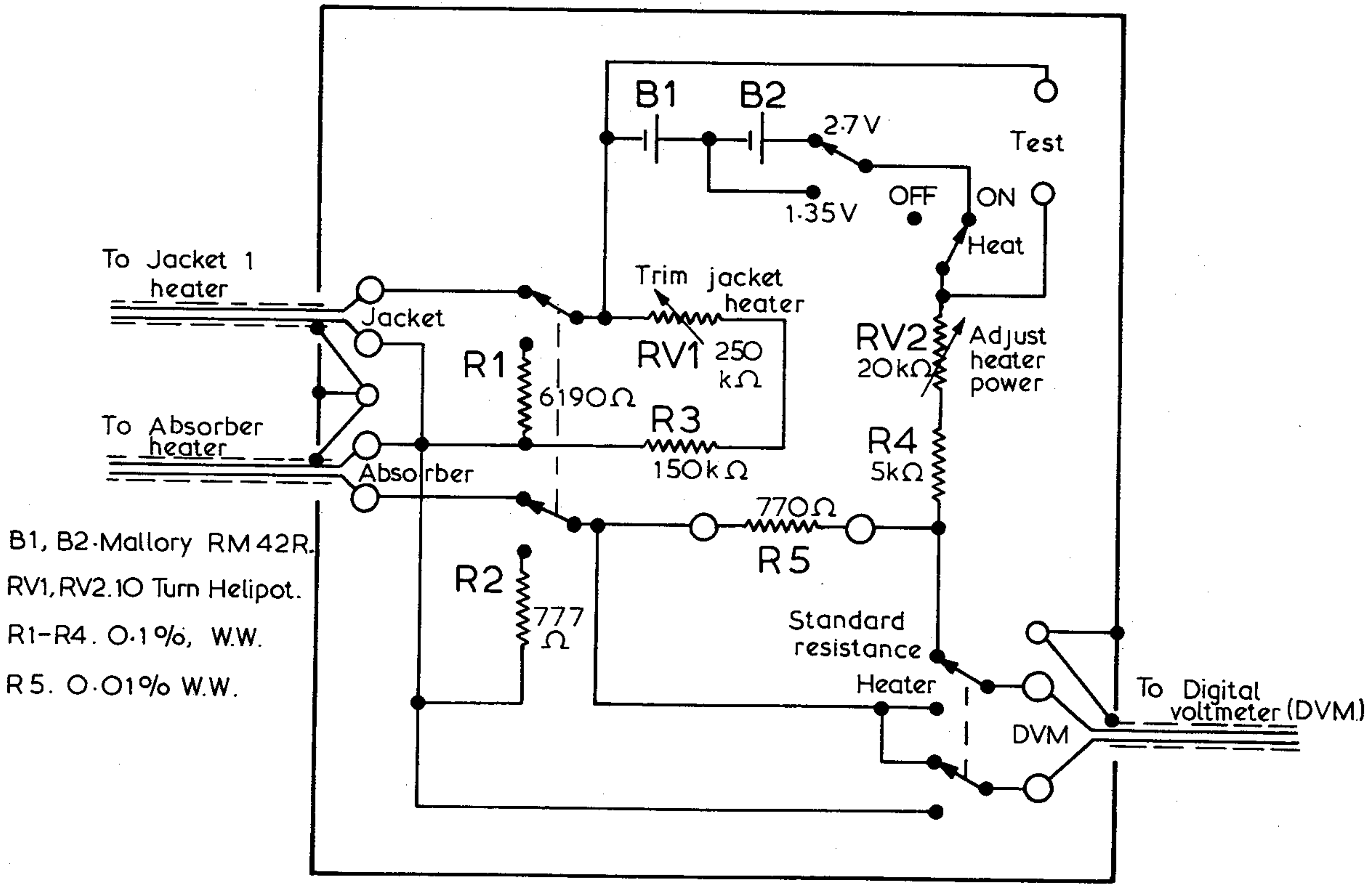


FIGURE 8. SCHEMATIC CIRCUIT DIAGRAM OF THE PRIMARY STANDARD



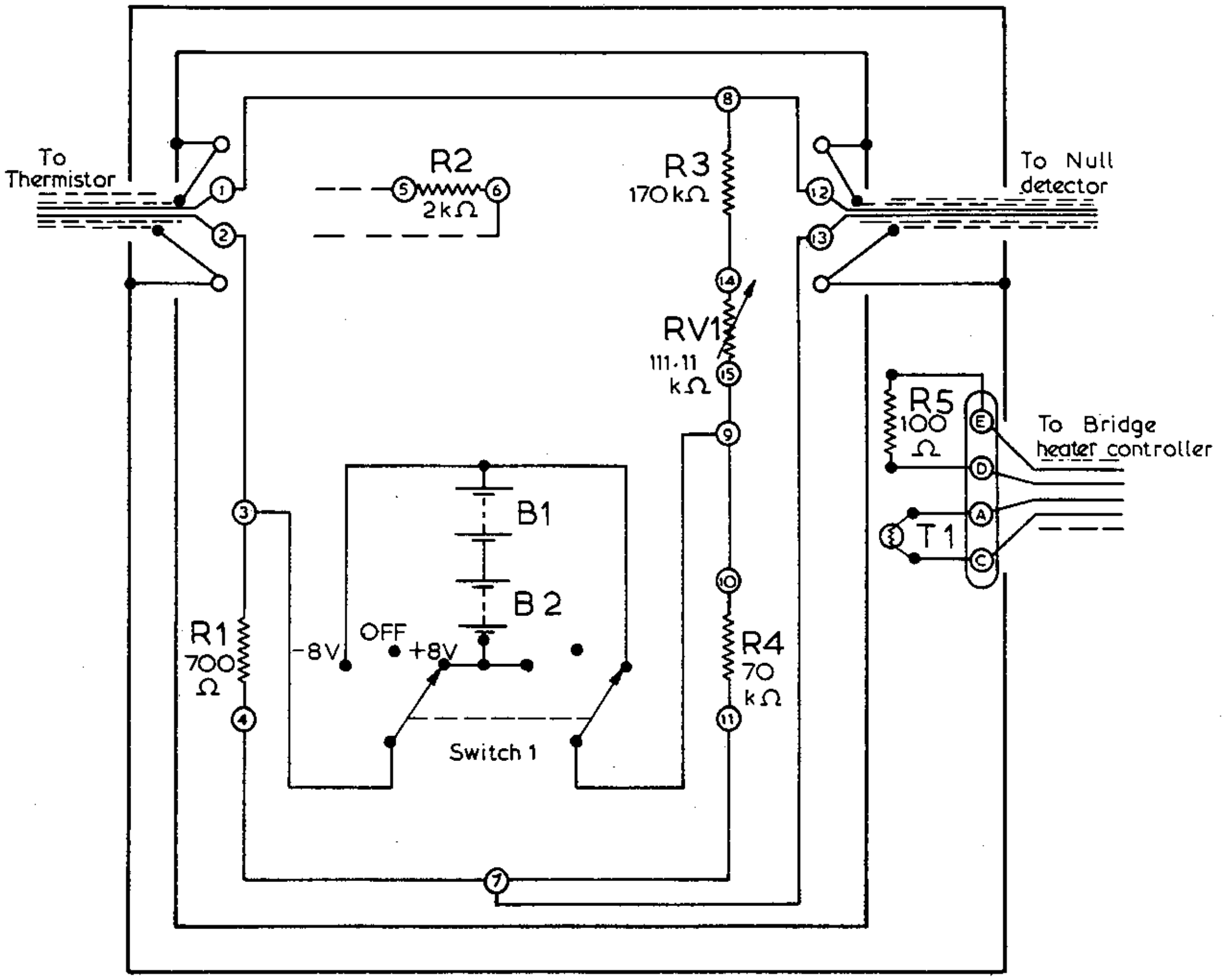
B1, B2·Mallory RM 42R.

RV1, RV2.10 Turn Helipot.

R1–R4. 0·1%, W.W.

R5. 0·01% W.W.

FIGURE 9. THE CALIBRATOR CIRCUIT



R5. Heater wire on outer case of bridge

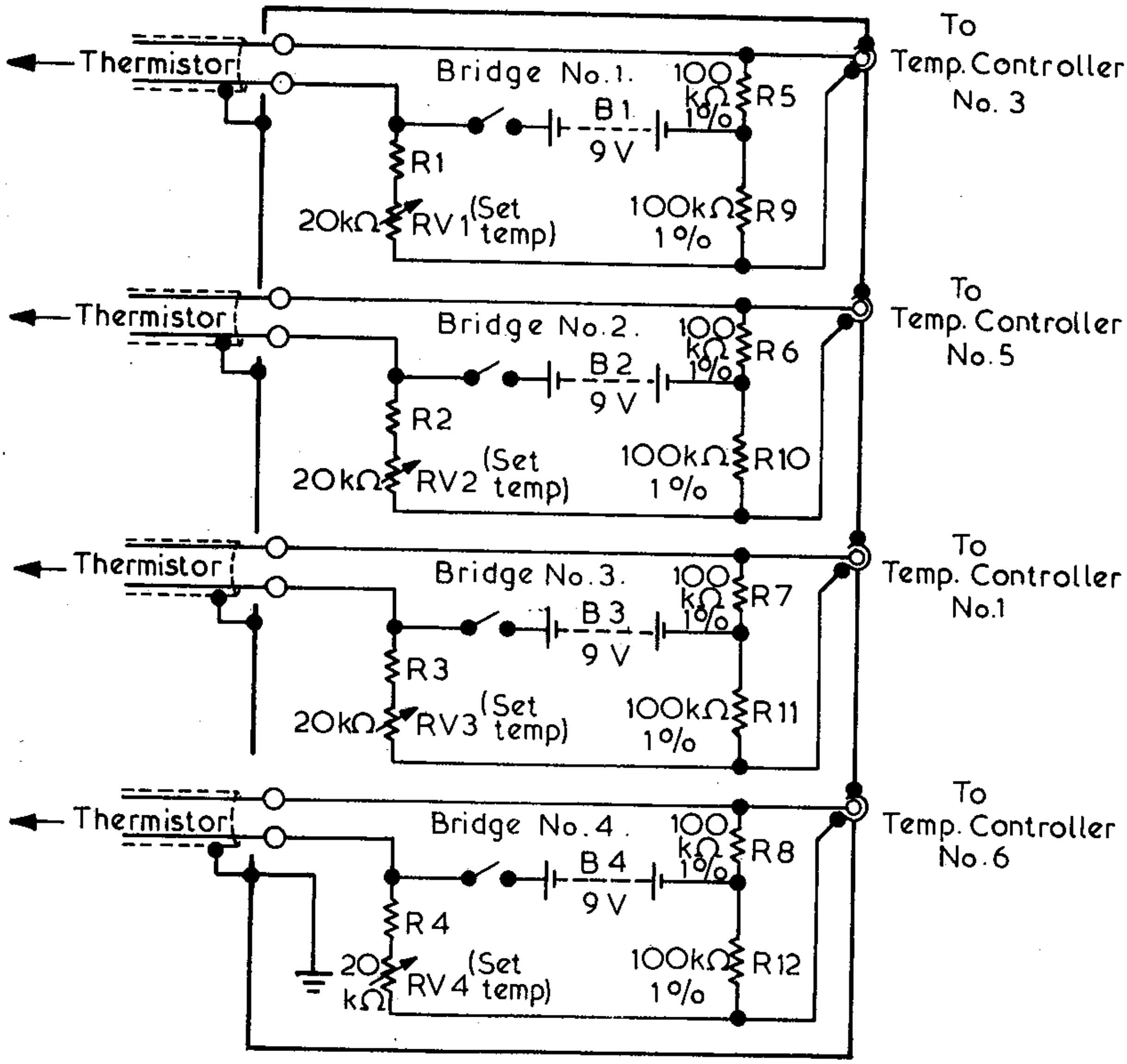
T1. Thermistor (100kΩ) which senses temperature of outer case of bridge

RV1. Leeds & Northrup decade resistance box type 4750.

R1-R4 Manganin wire wound resistors, ·05% tolerance.

Numbered terminals are low thermal type.

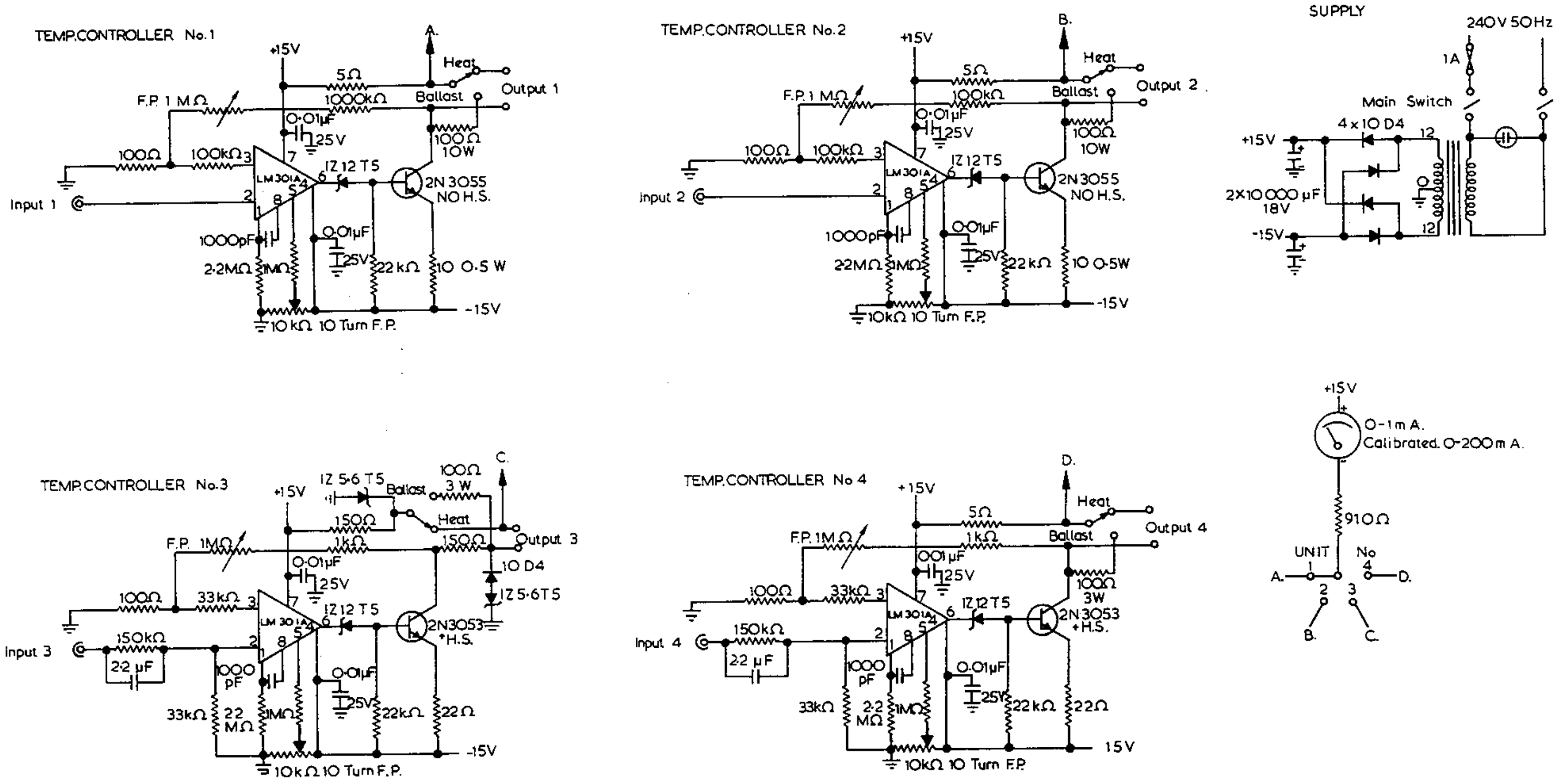
FIGURE 10. THE CIRCUIT USED IN BRIDGES 5 AND 6 (FIGURE 7)



R1 — R4 : Selected to suit thermistor.

RV1— RV4: 10 Turn Helipot

FIGURE 11. CIRCUIT DIAGRAMS OF BRIDGES 1 TO 4 (FIGURE 7)



F.P. =Front Panel screwdriver adjustment with pot lock

All resistors 0·125 W unless otherwise specifed.

H.S.=Heat Sink.

FIGURE 12. CIRCUIT DIAGRAMS OF TEMPERATURE CONTROLLERS NOS. 1 TO 4

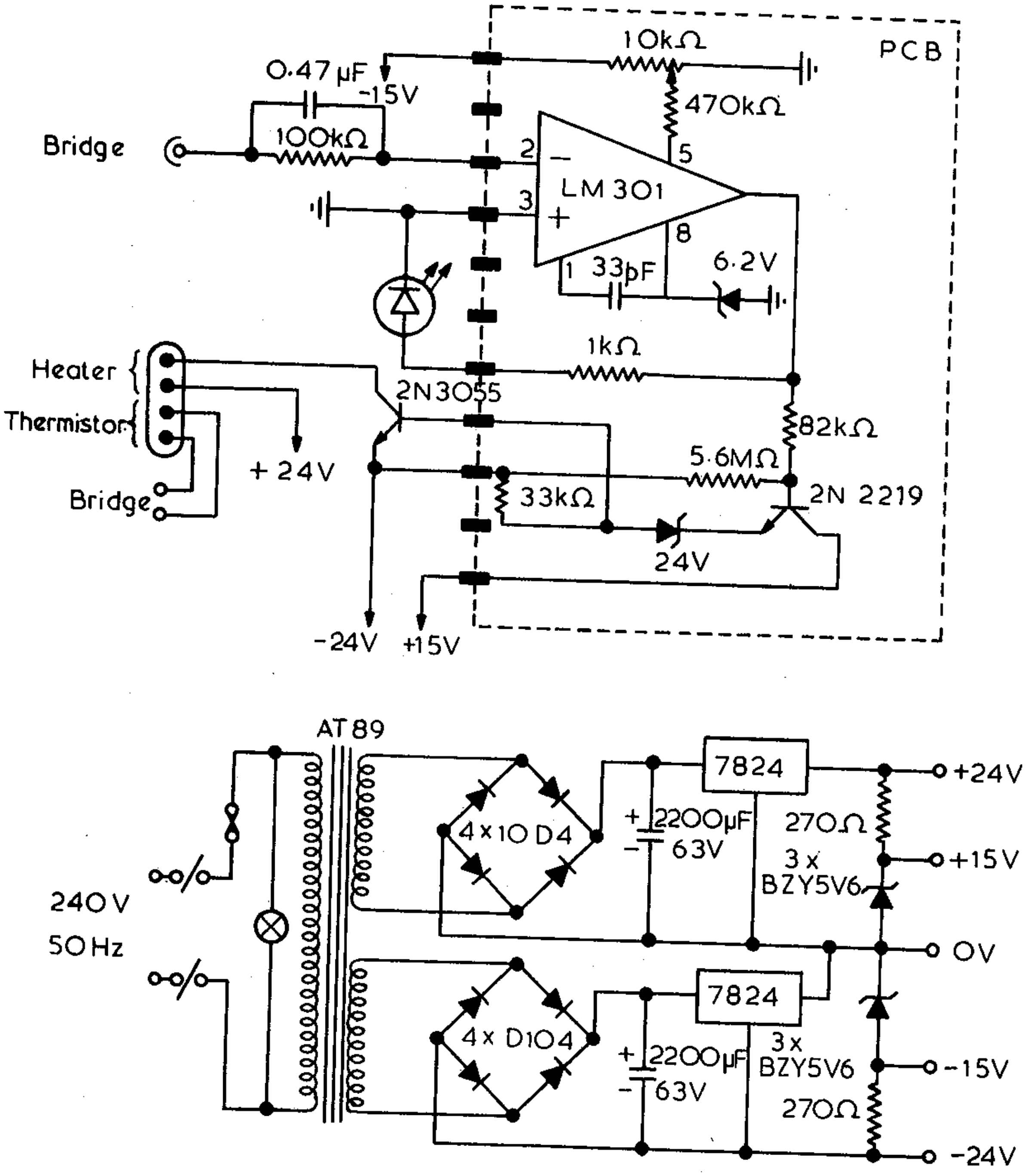
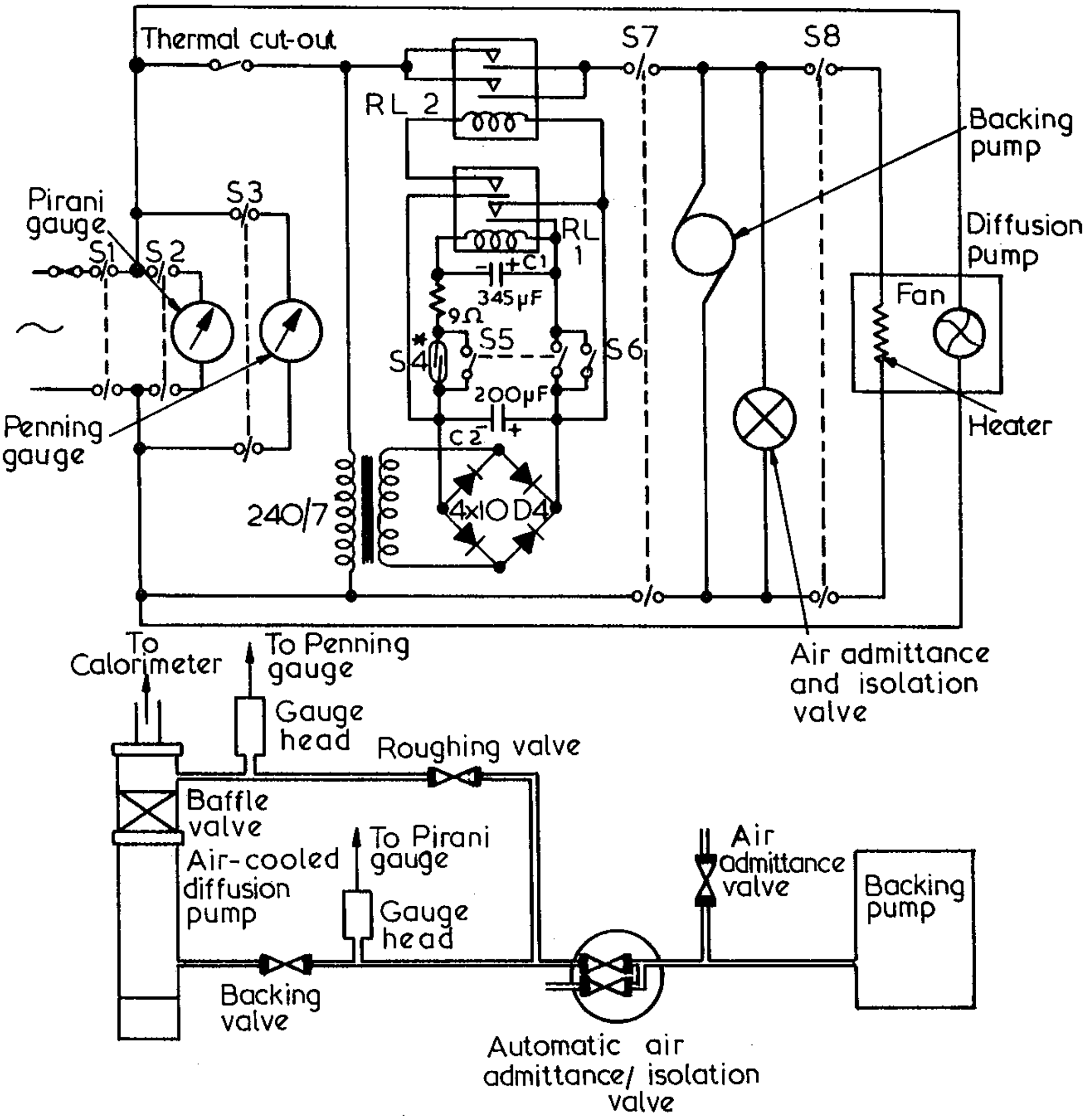


FIGURE 13. CIRCUIT FOR TEMPERATURE CONTROLLERS NOS. 5 AND 6 (FIGURE 7)



* Reed switch operated by magnet on backing pump drive pulley
Opens if drive belt fails and closes down pump

FIGURE 14. VACUUM PUMP SYSTEM

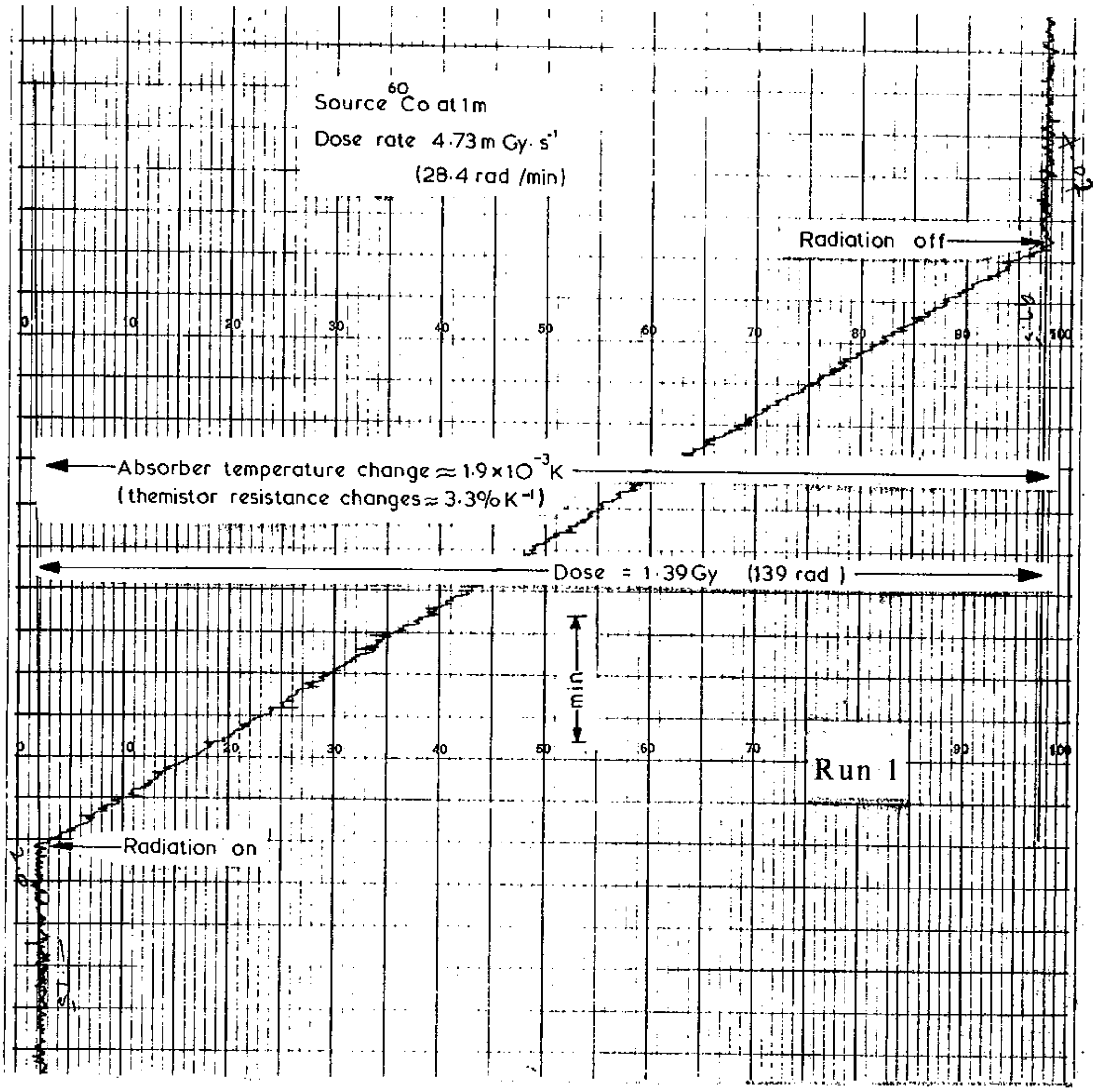


FIGURE 15. RECORD OF A RADIATION HEATING RUN

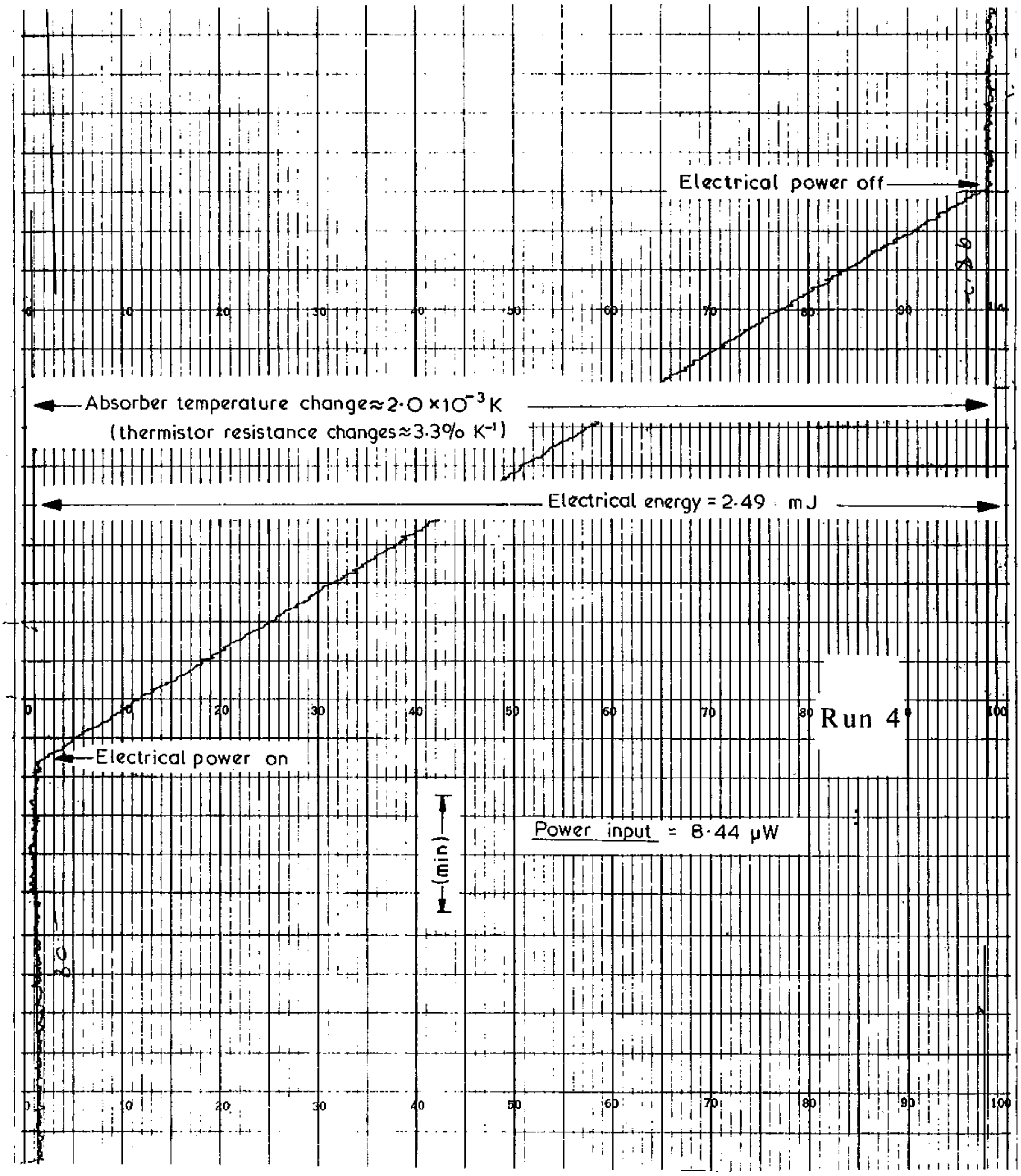


FIGURE 16. RECORD OF AN ELECTRICAL CALIBRATION RUN