

A118608260

AAEC/E627



AAEC/E627

AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS RESEARCH LABORATORIES

CALIBRATION AND OPERATION OF THE AAEC WORKING STANDARD
OF MEASUREMENT FOR THE ACTIVITY OF RADIONUCLIDES
PART I : THE MEASUREMENT SYSTEM

by

D.F. URQUHART

MAY 1986

ISBN 0 642 59831 2

AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS RESEARCH LABORATORIES

CALIBRATION AND OPERATION OF THE AAEC WORKING STANDARD
OF MEASUREMENT FOR THE ACTIVITY OF RADIONUCLIDES .
PART I : THE MEASUREMENT SYSTEM

by

D.F. URQUHART

ABSTRACT

A pressurised $4\pi\gamma$ ionisation chamber is used by the AAEC as a working standard of measurement for the activity of radionuclides. The instrument has a high degree of stability and the uncertainty in its activity measurements is only marginally greater than that of the primary standards used in its calibration.

This report details the method of calibration for a set of known, standardised isotopes, and extends the usage of the ion chamber to other isotopes by an interpolation technique. Particular attention is paid to eliminating changes in calibration due to instrumental variations with time.

The measurement system is straightforward in operation, giving best results for γ -emitting isotopes with energies above 200 keV and minimum activity of the order of 1 MBq.

National Library of Australia card number and ISBN 0 642 59831 2

The following descriptors have been selected from the INIS Thesaurus to describe the subject content of this report for information retrieval purposes. For further details please refer to IAEA-INIS-12 (INIS: Manual for Indexing) and IAEA-INIS-13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

AAEC; ACCURACY; CALIBRATION; CALIBRATION STANDARDS; CESIUM 134; CESIUM 137; COBALT 60; BARIUM 133; EXPERIMENTAL DATA; GAMMA RADIATION; IONIZATION CHAMBERS; RADIOACTIVITY; RADIUM 226

CONTENTS

1. INTRODUCTION		1
2. THE AAEC WORKING STANDARD		1
3. MEASUREMENT PROCEDURE		1
3.1 Theory		1
3.2 Practice		3
3.3 Accuracy		3
4. DIRECT CALIBRATION		4
4.1 Standardisation of Ra Reference Sources		4
4.2 Calibration Factors		5
5. CALIBRATION BY INTERPOLATION		5
6. SUMMARY		6
7. ACKNOWLEDGEMENTS		6
8. REFERENCES		6
Table 1	Radium reference sources	7
Table 2	Radium reference source currents (measured August 1984)	8
Table 3	Comparison of radium reference source current measurements	8
Table 4	Ion chamber calibration factors (measured Aug-Sept 1984)	9
Table 5	Calibration factor i_c for ion chamber No. 1729	10
Figure 1	TPA ionisation chamber	11
Figure 2	Working standard of activity	12
Figure 3	First approximation to the calibration curve for the TPA ion chamber No. 1729 using monoenergetic gamma emitters	13
Figure 4	Third approximation to the calibration curve for the TPA chamber 1729 using monoenergetic emitters and selected energies from multi-energy emitters	14

1. INTRODUCTION

National primary standards of measurement for physical quantities are not always suitable for the routine calibration of secondary standards. It is therefore common practice to use a working standard as the first step following primary standardisation, in the dissemination of standards of measurement throughout the community. A working standard must be checked from time to time against the national primary standard; therefore it need not be an absolute instrument. It must, however, be capable of making comparative measurements with a high degree of long-term stability, and should be as simple as possible.

Primary standards of activity of radionuclides are usually complex procedures involving the counting of emitted nuclear particles or photons from specially prepared thin sources. The end result of a standardisation is usually a value for the specific activity of a solution of the nuclide contained in a sealed glass ampoule or vial. Rather than repeat this counting procedure every time a new solution of the isotope is to be standardised, a working standard instrument is required to provide a simple measurement of activity by comparison with a standardised source, or an instrument calibration factor derived from a primary standard of activity is used.

Radionuclides that emit gamma or bremsstrahlung radiation require a thick-walled gas ionisation chamber as a working standard. Essentially, this instrument consists of a large volume chamber, a means of locating sources in a reproducible geometry, and a device for measuring the ionisation current with a high degree of reproducibility.

2. THE AAEC WORKING STANDARD

The best geometrical efficiency and an easily reproducible geometry is obtained by placing the source inside the chamber at the centre of the ionised gas-filled volume. The chamber efficiency for a given volume can be further increased by pressurising the gas.

The TPA ionisation chamber [Sharpe and Wade 1951] shown in figure 1 incorporates these features and forms the basis of the AAEC working standard which was implemented by G.C. Lowenthal and colleagues in 1965. The re-entrant chamber provides an almost 4π geometry and is filled with argon to a pressure of about 20 atmospheres (~ 2026 kPa). Perspex holders have been made to allow source solutions, contained in 3.6 mL glass ampoules or 10 mL vials, to be introduced to the chamber. Since 1983, the adjustment of the source holder has been checked from time to time in a brass depth gauge to ensure good reproducibility of source position in the chamber. The mild steel re-entrant thimble (i.d. 25 mm) has a wall thickness of 0.8 mm.

Ionisation currents are measured by an electrometer operating in the rate of charge mode (figure 2). The output appears as a voltage ramp across a feedback capacitor C. This is applied to a voltage comparator which senses when the ramp reaches a lower threshold voltage V_1 , and passes a starting pulse to an electronic timer. The comparator later senses when the ramp reaches an upper threshold V_2 , and stops the timer. The time interval Δt recorded by the timer is the time taken for the capacitor C to charge through the voltage interval $\Delta V = V_2 - V_1$ and is inversely proportional to the ionisation current I .

3. MEASUREMENT PROCEDURE

3.1 Theory

The simplest way of using the TPA ionisation chamber would be to compare a known mass M of the unknown solution (e.g. ~ 3.6 g in a glass ampoule) with an approximately equal mass of a standardised solution of the same isotope. The specific activity a of the unknown mass is then given by

$$a = \frac{A_m}{M} ,$$

where

$$A_m = \frac{I'_m - I_b}{I'_s - I_b} \cdot A_s \exp\left[-\frac{\ln 2}{T}(t_o - t_m)\right] , \quad (1)$$

where A_m is the activity of the source to be measured at the time of measurement t_m ; A_s is the activity of the standard source at the time of standardisation t_o ; T is the half-life of the radionuclide; I'_m is the ionisation current observed when the source to be measured is introduced to the chamber; I'_s is the current due to the standard source and I_b is the current due to background radiation (both sources completely shielded from the chamber).

This method can be applied only to those few radionuclides with half-lives long enough to permit the storage of standardised solutions over reasonably long periods. A second disadvantage is that errors in the decay

correction term may be large if $(t_o - t_m)$ is large compared with the half-life.

An alternative procedure, applicable to all gamma-emitting nuclides, is to measure the specific ionisation current i_c for each nuclide as soon as possible after a primary standardisation has been made. In this case

$$i_c = \frac{I'_s - I_b}{A_s} \exp \left[\frac{\ln 2}{T} (t_o - t_c) \right] ,$$

where t_c is the calibration time (*i.e.* the time of measurement of i_c), and the other symbols are as defined as above. In this case, $t_o - t_c$ can be $\ll T$, so decay correction errors are negligible.

This calibration factor can then be used to measure the activity A_m of an unknown solution of the isotope at any later time t_m since

$$A_m = \frac{I'_m - I_b}{i_c} .$$

The method is dependent on the long-term stability of the sensitivity of the ion chamber and, in this respect, is inferior to the first method (equation 1). The dependence on ion chamber sensitivity variations can be overcome by the use of a long half-life reference source in both calibration and measurement procedures. This is the method used at Lucas Heights and in most other national standards laboratories.

Radium-226 ($t_{1/2}$, 1600 years) is suitable as a reference source provided that it is completely sealed against leakage of its gaseous daughter product, radon. The sources used at Lucas Heights are doubly encapsulated and leak tested. A minor problem is that complete secular equilibrium between ^{226}Ra and all its daughters may not have been reached when the encapsulated isotope is first put into service as a reference source. This can lead to an anomalous gamma decay rate owing to build-up of certain daughter products, resulting in an effective half-life less than 1600 years. This effect is quite minor and is alleviated by the procedures described in section 4.

In this method, the activity of an unknown solution can be measured at any time t_m by comparing it with a radium reference source. In this case

$$A_m = \frac{I'_m - I_b}{I'_r - I_b} \cdot \frac{I_r}{k_r} \cdot \frac{1}{i_c} , \quad (2)$$

where I_r is the net ionisation current due to the Ra reference source at the time t_c (the calibration factor i_c for this isotope was measured); I'_r is the observed current (including background) due to the reference source at time t_m ; k_r is the small correction factor for the decay of ^{226}Ra , that is,

$$\exp \left[\frac{\ln 2}{T_r} (t_m - t_c) \right] ;$$

and T_r is the ^{226}Ra half-life. Equation 2 can be modified to suit the rate of charge method described in section 2. Since

$$I'_m - I_b = \frac{C \Delta V}{\Delta t_m} - \frac{C \Delta V}{\Delta t_b}$$

and

$$I'_r - I_b = \frac{C \Delta V}{\Delta t_r} - \frac{C \Delta V}{\Delta t_b} ,$$

we have

$$A_m = \left[\frac{\Delta t_b - \Delta t_m}{\Delta t_b - \Delta t_r} \right] \frac{\Delta t_r}{\Delta t_m} \cdot \frac{I_r}{k_r} \cdot \frac{1}{i_c} \quad (3)$$

which can be simplified to

$$A_m = \frac{\Delta t_r}{\Delta t_m} \cdot \frac{I_r}{i_c} \cdot \frac{k_b}{k_r} , \quad (4)$$

where the subscripts r , m and b refer to the reference source, the source being measured and the background, and k_b is a background correction factor such that

$$k_b = \frac{\Delta t_b - \Delta t_m}{\Delta t_b - \Delta t_r} \quad (5)$$

It is implicit in equation 3 that all values of Δt are measured under identical instrumental conditions, *i.e.* the same integrating capacitor and same electrometer sensitivity. In practice, however, the background charging time Δt_b may be measured with a smaller capacitor or more sensitive electrometer range to avoid unduly long charging times. It is a simple matter to correct such measurements to the required instrumental conditions to calculate the value of k_b appropriate to equation 4. Since k_b is typically between 1.01 and 0.99 and often much closer to 1.0, nominal values of capacitance or electrometer range are sufficient to calculate k_b with the required degree of accuracy.

3.2 Practice

The simple procedures described in this section have been adopted to optimise measurement accuracy in the application of equation 4. The measurement of activity reduces to a simple comparison of the capacitor charging times Δt_r and Δt_m , and these procedures minimise the effects of instrumental drift and non-linearity on the ratio $\Delta t_r/\Delta t_m$.

Errors due to instrumental non-linearity tend towards zero as $\Delta t_r/\Delta t_m$ approaches 1 and, since a wide range of source activities are measured, it is preferable to employ a number of reference sources with different activities. For example, a series of sources Ra1, Ra2, Ra3 ... such that the activity of Ra2 is approximately three times that of Ra1, Ra3 $\sim 3 \times$ Ra2, Ra4 $\sim 3 \times$ Ra3 ... ensures that $\Delta t_r/\Delta t_m$ is always between $1/\sqrt{3}$ and $\sqrt{3}/1$ when the appropriate reference source is used.

The reference sources listed at the end of table 1 are currently in use and cover the range of activities normally required in this laboratory. The table shows the radium content (μg) of the source and its uncertainty (where stated by the supplier). Nominal charging times for the reference sources are also listed in table 1, and are for the 0.8 V interval ΔV usually employed. These data are used to select the appropriate reference source for each measurement. Most measurements are made using capacitor C2 which provides an integrating capacitance of 3022 pF, including approximately 22 pF of stray capacitance associated with electrometer input circuitry. A larger capacitor, C3, is sometimes required for particularly strong sources and in some cases a smaller capacitor C1 is required if a less sensitive electrometer is used during maintenance of the Carey model 401 electrometer.

An advantage of this procedure is that errors caused by inaccuracy in background measurements are also reduced. It can be seen from equation 5 that the background correction factor k_b approaches 1.0 as Δt_r approaches Δt_m . Values of charging times for background are shown in table 1 under the heading 'CAPACITOR C2'; it can be seen that background activity is roughly equivalent to 50 ng of ^{226}Ra .

The effect of instrumental drift can be reduced by interposing measurements of source charging times between measurements of Ra reference charging times and selecting instrumental parameters to give the shortest charging times consistent with good timing accuracy. Experience has shown that with this equipment, charging times between 100 and 300 s give optimum results.

On the basis of the above considerations, the following procedure has been adopted:

- Select electrometer range and capacitor value such that the charging time for the source is in the range 100 to 300 s.
- Use table 1 to select a radium reference source such that $\Delta t_r/\Delta t_m$ is as close as possible to 1.0.
- Place the selected Ra reference in the ion chamber and measure Δt_r at least twice.
- Place the source in the ion chamber and measure Δt_m at least four times.
- Place the Ra reference in the chamber and measure Δt_r at least twice.
- Use mean values of Δt_r and Δt_m (adjusted for source decay) in equation (4).

3.3 Accuracy

The TPA ionisation chamber has a high degree of stability and reproducibility. The uncertainty of measurements is therefore only marginally greater than the uncertainty in the calibration factor used. When the instrument is calibrated directly (see section 4), uncertainty in the calibration is only marginally greater than that of the primary standardisation. This varies from nuclide to nuclide, but is generally better than ± 1 per cent 1σ level.

When the calibration factor is determined by the interpolation procedure described in section 5, its uncertainty is essentially the combination of uncertainties associated with the Γ value of figure 4 and the published decay scheme data, both of which vary from nuclide to nuclide. In general, the overall uncertainty in interpolated calibration factors is better than ± 2 per cent, but may be as high as ± 5 per cent for some complex decay schemes.

4. DIRECT CALIBRATION

The radionuclide ^{60}Co was chosen as a convenient benchmark, linking the ionisation chamber with primary standards of activity in such a way that calibration factors for all gamma-emitting nuclides can be normalised with respect to it. Cobalt-60 was chosen because it has a long half-life and a simple, well-known decay scheme which allows it to be standardised accurately by absolute counting techniques.

The first high precision determination of the calibration factor i_c for ^{60}Co was made in August 1978. The value obtained then has been adopted as a benchmark calibration constant for the useful life of this particular chamber. For ^{60}Co sources in 3.6 mL standard NBS glass ampoules:

$$i_c = 63.770 \text{ pA MBq}^{-1} \text{ exactly on 1 August 1978.}$$

All Ra reference source current determinations are normalised to the same date using a half-life of *exactly* 1600 years. This convention allows all activity measurements made with this chamber to be normalised, with respect to chamber performance, to the chamber sensitivity pertaining to the 1 August 1978 measurement of i_c for ^{60}Co .

As was mentioned in section 3.1, the Ra reference sources may be subject to anomalous decay rates which produce small discrepancies in the 1600 year half-life. It is necessary, therefore, to restandardise the reference sources from time to time to ensure continuing consistency with the benchmark ^{60}Co calibration. Experience over the last seven years indicates that in future it will be sufficient to restandardise the reference sources at intervals of not less than five years. The last such standardisation was made in August 1984; the procedure and results are described in section 4.1. However, should an improved absolute counting technique be developed, any improvement in the accuracy of primary standards of ^{60}Co should be passed on to the ionisation chamber measurements by restandardising the Ra reference sources with new ^{60}Co standard solutions (see section 4.1).

4.1 Standardisation of Ra Reference Sources

The initial measurements of Ra reference source currents were made in 1978 in absolute terms, whereas the present practice is to measure a *conventional* current consistent with the benchmark ^{60}Co calibration. The August 1984 standardisation used the procedure described below.

A set of six standardised ^{60}Co sources in standard NBS glass ampoules were prepared to match the six Ra reference sources then in use. That is to say, each ^{60}Co source had an activity able to produce approximately the same ionisation current as one of the reference sources. Each reference source was carefully compared with its matching ^{60}Co standardised solution in the ion chamber. Equation 4 was then solved for I_r .

$$I_r = \left\{ \frac{\bar{\Delta}t_m}{\Delta t_r} \right\} A_m \cdot i_c \cdot \frac{k_r}{k_b} ,$$

where I_r is the Ra reference source current (pA) normalised for decay to 1 August 1978; $(\bar{\Delta}t_m/\bar{\Delta}t_r)$ is the measured ratio of the mean capacitor charging time of the ^{60}Co source to the mean radium reference source charging time at the time of measurement t_m ; A_m is the activity of the standardised ^{60}Co source (MBq) at time t_m ; i_c is the 63.770 pA MBq $^{-1}$; k_b is the background correction factor; and $k_r = \exp(\lambda T)$ where λ is the decay constant for ^{226}Ra such that

$$\lambda = \frac{\ln 2}{1600} \text{ y}^{-1} ,$$

and T is the time in years between 1 August 1978 and t_m . Both $\Delta t_m/\Delta t_r$ and k_b were close to 1.0, in accordance with the recommendations given in section 3.2.

The high degree of uniformity of dimensions of the NBS ampoules is such that errors due to variation of attenuation of the ^{60}Co radiation in the walls of different ampoules, and other dimensional effects, are insignificant.

Results for the 1984 measurement of Ra reference currents are listed in the last column of table 2 and compared with earlier measurements in table 3. The small differences in measurements may be due to a combination of several factors:

- (i) anomalous decay rates;
- (ii) the use of different measurement methods; and
- (iii) experimental error.

4.2 Calibration Factors

Direct calibration of the ionisation chamber for any gamma-emitting nuclide is made by preparing a standardised solution of the nuclide in a standard glass ampoule or vial and comparing it in the chamber with the appropriate Ra reference. Where possible, the level of activity of the standardised source is made to match one of the reference sources — preferably one of medium strength such as Ra5 (table 1). The nominal source activity can be calculated from published gamma decay data and the chamber calibration curve (figure 4) described in section 5.

Equation 4 is also used to calculate the calibration factor i_c . When the equation is re-arranged, we get

$$i_c = \frac{\bar{\Delta}t_r}{\bar{\Delta}t_m} \cdot \frac{I_r}{A_m} \cdot \frac{k_b}{k_r} ,$$

where the symbols $\bar{\Delta}t_m$, A_m and i_c , now refer to the nuclide in question and all the other terms are as before.

At least two calibration factors are required for each nuclide — one for 3.6 mL solutions in standard glass ampoules and one for 10 mL solutions in standard glass vials. For some nuclides, a third calibration factor may be required for a special source configuration. For example, this chamber is often used to measure the ^{198}Au activity of gold wires or foils used as reactor neutron flux monitors.

A new calibration factor was recently made for ^{226}Ra ampoule sources and ampoule sources of ^{133}Ba , ^{134}Cs and ^{137}Cs and for ^{60}Co vials have been recalibrated. The results of these measurements are shown in table 4.

The ^{133}Ba sources were standardised at Lucas Heights as part of a recent international comparison [Rytz 1984] and the ^{137}Cs and ^{134}Cs sources were standardised during an earlier international comparison of ^{137}Cs [Rytz 1983a]. A certified ^{226}Ra solution obtained from the Radiochemical Centre, Amersham, UK, was used for the ^{226}Ra calibration.

The results of all direct chamber calibrations made at the Lucas Heights Research Laboratories so far are listed in table 5.

5. CALIBRATION BY INTERPOLATION

It may be necessary to use the ionisation chamber to measure the activity of nuclides for which no calibration factor has been measured. In these cases, it is possible to estimate the required factor by interpolation from known calibration factors for other nuclides. The method adopted is similar to one used by Rytz [1983b] at the Bureau International des Poids et Mésures (BIPM) in Paris.

For those nuclides which emit photons of one energy only, the calibration factor will probably be related to the product of the photon energy E (keV) and its intensity I per cent (number of photons \times 100 per disintegration), so the estimated calibration factor i'_c is given by:

$$i'_c = KEI/100 \tag{6}$$

where K is a constant for this chamber.

Cobalt-60 has a benchmark calibration factor of $63.770 \text{ pA MBq}^{-1}$ and it is well known that ^{60}Co emits two gammas of almost equal intensity (99.90 and 99.98 per cent) and similar energies (1173.21 and 1332.47 keV). The chamber response to ^{60}Co can therefore be expected to be the same as for a hypothetical nuclide emitting a single energy of 1252.84 keV with an intensity of 199.88 per cent. These data were used to calculate the value of K in equation 6:

$$K = \frac{63.770 \times 100}{1252.84 \times 199.88} = 2.546 \times 10^{-2} \text{ pA keV}^{-1} \text{ MBq}^{-1}$$

for ^{60}Co photons.

With this value of K , equation 6 was used to calculate i'_c for monoenergetic emitters whose 'true' calibration factor i_c has been measured. The factor $R = i_c/i'_c$ was then plotted as a function of photon energy, as shown in figure 3. The curve fitted to these points provides a rough first approximation to the 'true' calibration factor curve. Such a curve can be used in conjunction with published decay scheme data to calculate the calibration factor for many gamma emitters. For a nuclide emitting n different photon energies, the calibration factor is given by

$$i_c = \frac{K}{100} \sum_{j=1}^{j=n} E_j I_j R_j \quad (7)$$

where E_j and I_j are the energies and intensities of the j^{th} gamma and R_j is the R value for the j^{th} gamma, read from the curve of figure 3.

Some standardised nuclides have one high intensity gamma and several low intensity gammas. In such cases, equation 7 is used to calculate the contribution to the ionisation chamber current from the low intensity gammas; the difference between this contribution and the measured i_c value yields an R value for the high intensity gamma energy. This procedure provides a second, closer approximation to the 'true' calibration curve.

Some other standardised nuclides emit one gamma energy above or below the energy range covered by the second approximation, and other gammas within that range. In these cases, the second approximation is used to calculate the contribution of the 'in range' energies which, with the measured i_c value, yields an R value for the 'out of range' energy. This produces the third approximation shown in figure 4. This calibration curve has been found to enable the measurement of the activity of many non-standardised nuclides most satisfactorily although further refinement will be possible as more nuclides are standardised.

The interpolative calibration procedure cannot be applied with confidence to gamma-emitting nuclides which also emit intense high-energy (>2 MeV) beta radiation. For these nuclides, the contribution to the ion current due to bremsstrahlung radiation generated in the source, ampoule and chamber wall cannot be estimated with sufficient certainty.

6. SUMMARY

In addition to maintaining Australia's national standard for the activity of radionuclides, the AAEC also maintains a working standard of measurement. The device which provides the working standard is a TPA pressurised $4\pi\gamma$ ionisation chamber. The techniques involved in calibration and operation of this ionisation chamber have been described in detail.

By use of an interpolation technique, the range of isotopes that may be standardised has been extended beyond those radioactive elements so that a direct calibration may be performed. The interpolation technique has been fully detailed and relevant data for the TPA ionisation chamber provided.

7. ACKNOWLEDGEMENTS

K. Mears carried out the measurements and provided further assistance in typing and debugging the computer programs. H. Wyllie and V. Page prepared and standardised the ^{60}Co sources and carried out the pre-1982 calibrations.

The recycling discriminator was designed and produced by the Applied Physics Division's Instrumentation Design Group.

8. REFERENCES

- Rytz, A. [1983a] - International comparison of activity measurements of a solution of ^{137}Cs (May 1982). BIPM-83/8.
- Rytz, A. [1983b] - The international reference system for activity measurements of γ -ray emitting nuclides. *Int. J. Appl. Radiat. Isot.*, 34(8)1047-1056.
- Rytz, A. [1984] - International comparison of activity measurements of a solution of ^{133}Ba . BIPM-84/5.
- Sharpe, J., Wade, F. [1951] - TPA Mk III ionization chamber. AERE EL/R806.

TABLE 1
CONTENTS IN μg OF RADIUM REFERENCE SOURCES AND NOMINAL CHARGING TIMES FOR CAPACITORS C1, C2 AND C3

Electrometer Range	Nominal Charging Time (s)/0.8 V						Range
	30 mV	100mV	300mV	1 V	3 V	10 V	
Capacitor C1 (1007+22 pF)							
Ra1	11	36	†108	363	1078	3627	*Ra2
*Ra2	-	-	-	-	-	-	Ra3
Ra3	2	5	16	53	159	535	Ra4
Ra4	<1	2	8	25	75	249	Ra5
Ra5	<1	<1	2	5	15	51	Ra6
Ra6	<1	<1	<1	2	5	18	Ra7
Ra7	<1	<1	<1	1	3	11	
Capacitor C2 (3000+22 pF)							
Background	~1020	~3400	~10 000	~34 000	~100 000	~340 000	Ra1
Ra1	32	106	319	1064	3186	10644	*Ra2
*Ra2	-	-	-	-	-	-	Ra3
Ra3	5	16	47	157	470	1570	Ra4
Ra4	2	7	22	73	219	730	Ra5
Ra5	<1	2	5	15	45	150	Ra6
Ra6	<1	<1	2	5	15	53	Ra7
Ra7	<1	<1	<1	3	9	31	
Capacitor C3 (100078+22 pF)							
Ra1	107	356	1068	3557	10678	35573	*Ra2
*Ra2	-	-	-	-	-	-	Ra3
Ra3	16	52	158	525	1575	5247	Ra4
Ra4	7	24	72	240	720	2404	Ra5
Ra5	2	5	5	50	150	499	Ra6
Ra6	<1	2	5	18	54	180	Ra7
Ra7	<1	1	3	10	31	103	
Ref.No.	Ra1	Ra2	Ra3	Ra4	Ra5	Ra6	Ra7
Activity (μg)	1.537	*	10.33	22.55	108.59	307.4	524.6
(Aug. 1978)	± 0.080		± 0.42	± 1.14	± 3.30	-	-

* To be purchased

† Box indicates optimum charging time

TABLE 2
RADIUM REFERENCE SOURCE CURRENTS
(measured August 1984)

⁶⁰ Co Ampoule Source (3.6 g)			Ra Reference Source		
No.	kBq on 12/11/78	No.	Ra(μg) on 1/8/78	<i>I_r</i> (pA) on 1/8/78	
24 A1 A3A	43.69 ± 0.06	Ra1	1.537 ± 0.077	2.269 ± 0.016	
		*Ra2			
24 A1 A3	243.7 ± 0.6	Ra3	10.33 ± 0.42	15.322 ± 0.07	
24 A1 A2	508.0 ± 0.1	Ra4	22.55 ± 1.14	33.182 ± 0.07	
24 A3	3056 ± 7	Ra5	108.59 ± 3.3	162.88 ± 0.07	
24 A2	8541 ± 20	† Ra6	307.4 ± ?	428.55 ± 0.12	
24 A2	8541 ± 20	Ra7	524.6 ± ?	784.77 ± 0.18	

*To be purchased; † Aged radium, purchased 1982.

TABLE 3
COMPARISON OF RADIUM REFERENCE SOURCE
CURRENT MEASUREMENTS

Year	Item	Ra1	*Ra2	Ra3	Ra4	Ra5	Ra6	Ra7
1978	<i>I_r</i> (pA) on 1/8/78	-	-	15.312	33.134	162.425	-	-
1981	<i>I_r</i> (pA) on 1/8/78	-	-	15.29	33.091	162.215	-	-
1982	<i>I_r</i> (pA) on 1/8/78	-	-	15.319	33.176	162.72	428.25	785.87
1984	<i>I_r</i> (pA) on 1/8/78	2.269 ± 0.016	-	15.322 ± 0.07	33.182 ± 0.070	262.88 ± 0.07	428.55 ± 0.12	784.77 ± 0.18
	Ra content (μg) on 1/8/78	1.537 ± 0.077	-	10.33 ± 0.42	22.55 ± 1.14	108.59 ± 3.3	307.4 -	524.6 -
	Ampoule equivalent (kBq) on 1/8/78	49.70 ± 0.49	-	335.4 ± 2.8	726.4 ± 5.3	3566 ± 25	9382 ± 66	17180 ± 120

* To be purchased

TABLE 4
ION CHAMBER CALIBRATION FACTORS
(measured August - September 1984)

Job Ref. No.	Nuclide	Source Type	Calibration		Ra Ref. Source Used
			Factor i_c (pA MBq ⁻¹)	σ (pA MBq ⁻¹)	
1287 B	⁶⁰ Co	vial	63.337	± 0.10	Ra5, Ra6
1287 C	¹³³ Ba	ampoule	12.573	± 0.05	Ra3
1287 D	¹³⁴ Cs	ampoule	44.374	± 0.20	Ra3
1287 E	¹³⁷ Cs	ampoule	16.374	± 0.21	Ra3
1287 F	²²⁶ Ra	ampoule	45.678	± 0.32	Ra1

TABLE 5*
CALIBRATION FACTOR i_c FOR ION CHAMBER 1729

*KI	Nuclide	Half-Life (d)	Ampoules (3.6 mL)		Vials (10 mL)	
			$i_c \pm \sigma$ (pA MBq ⁻¹)	Date Measured	$i_c \pm \sigma$ (pA MBq ⁻¹)	Date Measured
4	²⁴¹ Am	158153	1.032	Pre-1982	0.9018	Pre-1982
8	⁵⁷ Co	290.9	6.270	"	6.159	"
10	^{99m} Tc	0.2508	5.846	"	5.743	"
12	¹³⁹ Ce	137.66	5.480	"	5.458	"
14	⁷⁵ Se	119.8	15.61	"	-	-
16	¹³³ Ba	3846	12.57 ± 0.05	1984	12.35	"
18	⁵¹ Cr	27.704	1.008	Pre-1982	1.0021	"
20	¹³¹ I	8.04	11.85	"	11.78	"
22	¹⁹⁸ Au	2.696	-	-	12.40	"
22	¹⁹⁸ Au		Wire in Vial		12.63	"
28	¹³⁷ Cs	11100	16.37 ± 0.21	1984	16.16	"
30	¹³⁴ Cs	754.4	44.37 ± 0.20	1984	44.00	"
32	²² Na	950.4	59.24	Pre-1982	58.76	"
34	^{110m} Ag	249.9	-	-	74.63	"
36	⁵⁴ Mn	312.5	23.27	"	23.10	"
38	⁴⁶ Sc	83.83	53.80	"	53.45	"
40	⁶⁵ Zn	243.9	15.14	"	15.06	"
42	⁵⁹ Fe	44.529	31.01	"	30.77	"
44	⁶⁰ Co	1925	† 63.770	-	63.34 ± 0.10	1984
46	⁸⁸ Y	106.64	65.39	"	65.04	Pre-1982
48	⁴² K	0.515	-	-	7.315	"
58	²²⁶ Ra	584400	45.68 ± 0.32	1984	-	-
60	³² P	14.29	0.1323	Pre-1982	-	-

*All the data in this table are included in the data base of the computer program MANIC. KI is the variable name of a code number used in MANIC for each nuclide.

† Benchmark factor for this chamber.

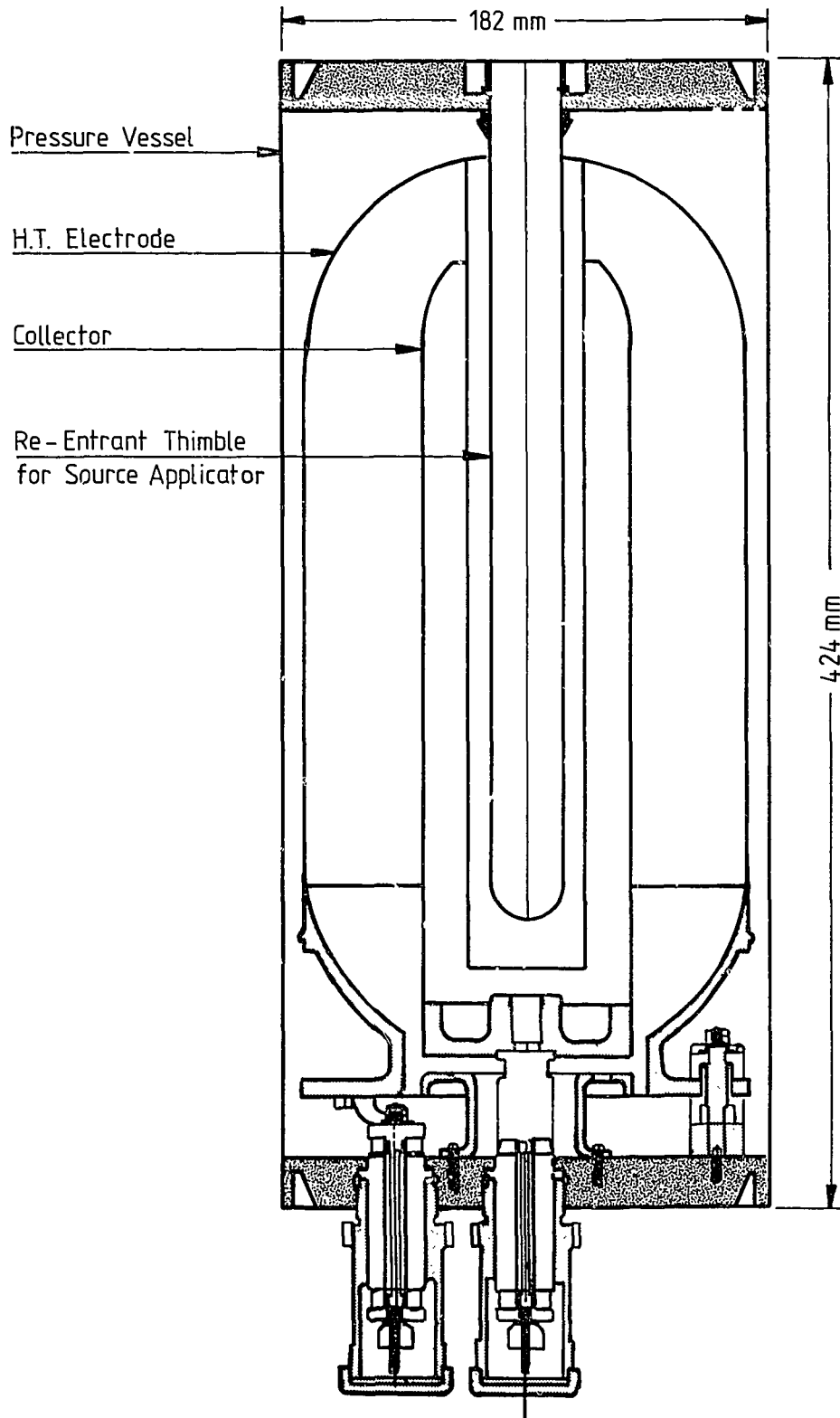


Figure 1 TPA ionisation chamber

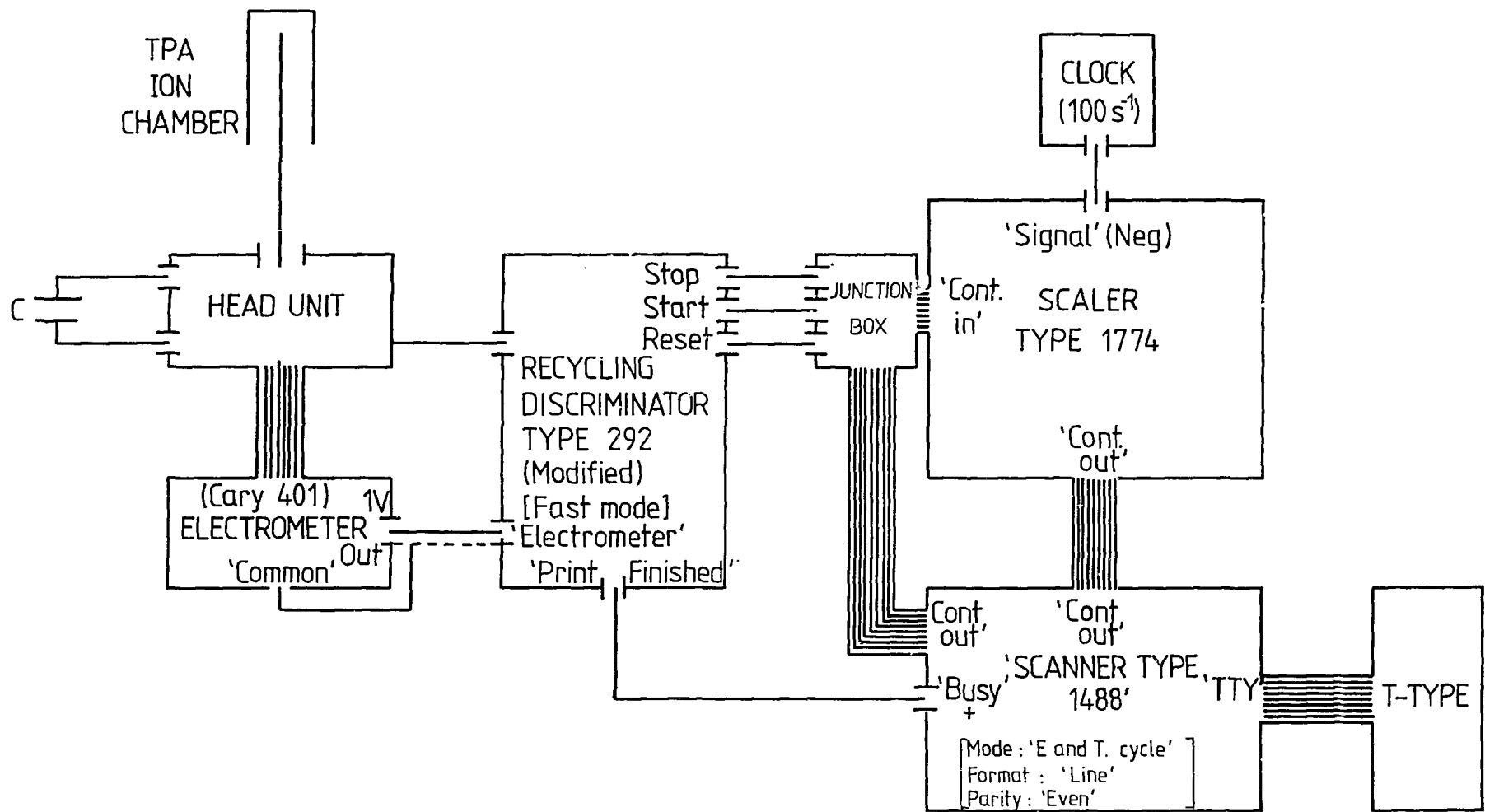


Figure 2 Working standard of activity

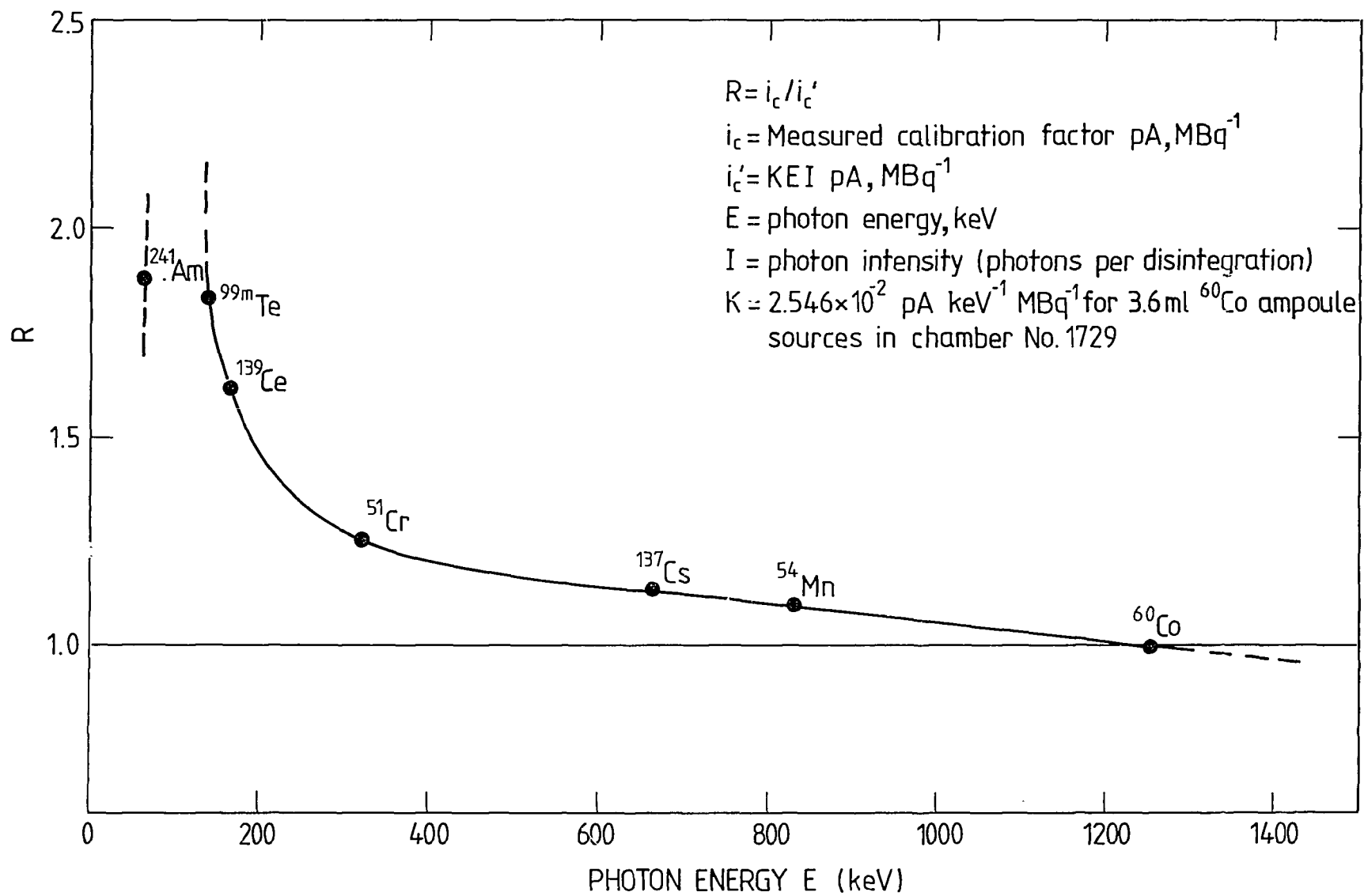


Figure 3 First approximation to the calibration curve for the TPA ion chamber No. 1729 using monoenergetic gamma emitters

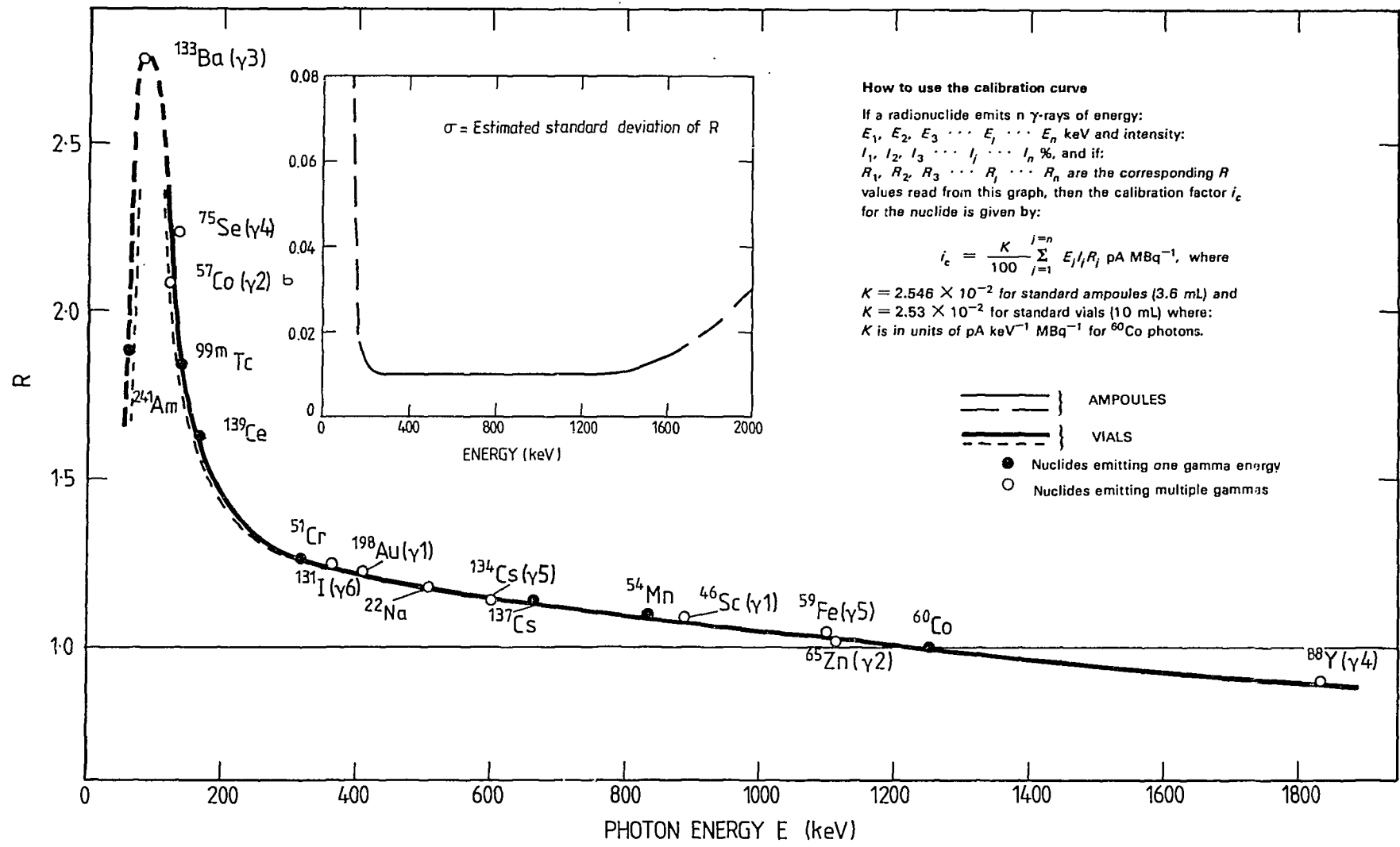


Figure 4 Third approximation to the calibration curve for the TPA chamber 1729 using monoenergetic emitters and selected energies from multi-energy emitters