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The Use of Relatively Small Sources for the Calibration of Area Survey Meters

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ABSTRACT

The contiguous portions method is a technique employed to calibrate surface contamination monitors when calibration sources having an active area greater than that of the detector are not available.

A series of experiments were undertaken to determine whether the method would be adversely affected by source and detector inhomogeneity, backscatter and repeated exposure to the edges of the calibration source. Comprehensive field trials compared the results of five laboratories performing contiguous portions calibrations to demonstrate the repeatability of the method. The additional uncertainty introduced to a calibration by the adoption of the contiguous portions method is of the order of 10 % when steps are taken to minimise a number of effects and detailed guidelines are followed.

Measurements made on a specially fabricated 500 x 500 mm source allowed validation of the method when detector responses from it were compared with those from a representative 100 x 100 mm piece of that source employed in the contiguous portions method.

A recommended protocol for the performance of the contiguous portions technique and guidance for the determination of additional error bounds are included.

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1 INTRODUCTION

1.1 SURFACE CONTAMINATION MONITORING

It is a statutory requirement, as described in Regulation 24 of the Ionising Radiations Regulations, 1985 ^[1], that all users of radioactive materials monitor for surface contamination. The instruments used for this purpose must be thoroughly examined and tested on a regular basis. The specific tests required are outlined in paragraphs 152 - 157 of the associated Approved Code of Practice ^[2] which also demands that all calibrations are traceable to national standards (paragraph 158).

Detailed guidance for the calibration of portable radiation monitors is contained in the HSE document HS(G)49^[3]; this guidance was adopted by most commercial calibration organisations during preparation of their calibration procedures. The acceptance criteria that are contained within HS(G)49 are centred around the confirmation that the present performance of a monitor does not differ significantly from either type tests or performance in previous annual tests. In order that such comparisons can be soundly made, it is important that calibrations are conducted in a reproducible manner. To this end, the preferred format for calibration sources is that of semi-infinite plane geometry where the active area of the source is sufficiently greater than that of the detector window area, such that if the source area was extended, it would not increase the detector response significantly.

Details of the required types, dimensions and characteristics of reference sources used in the calibration of surface contamination monitors are given in ISO 8769 parts 1 ^[4] and 2 ^[5]. A variety of sources are available commercially and a number of accredited calibration facilities exist in the UK. Users may of course produce their own sources and calibration protocols but they would be required to demonstrate their suitability to meet the statutory requirements.

In recent years, there has been a trend towards the use of large area survey meters resulting from improvements in manufacturing technology and their increased availability and convenience. Consequently, reference sources of ever increasing active area are demanded for the calibration of such monitors. Beyond a certain limit, use of such sources becomes impractical due to manufacturing constraints on uniformity and the cost of purchase.

This problem was recognised in the development of HS(G)49 and was accommodated by the incorporation of the contiguous portions method. Although the principle of this method is inherently sound, there had been no experimental validation or estimation of the associated uncertainties. Consequently, users of the contiguous portions method were unable to determine the accuracy and uncertainty involved with their calibrations. This raised the important question of whether users would be able to demonstrate compliance with their statutory obligations.

As a result of user concerns, a project was established in the 1995-98 Ionising Radiation Metrology Programme at the National Physical Laboratory (NPL), funded by the National Measurement System Policy Unit (NMS-PU) as part of their support to maintaining the National Measurement System infrastructure in the UK.

The objectives of the project were to:

define the best pragmatic protocol for using sources of 100 x 100 mm and 100 x 150 mm to calibrate portable radiation contamination monitors of larger area than such sources;

define the additional error bounds which may be typically expected from using the protocol.

A collaborative project was developed, headed by NPL, comprising members from several external organisations providing a representative cross-section of interested parties. This included users of radiation monitors, calibration facilities, quality assessors and probe manufacturers. The participants in the project are contained in Appendix I.

1.2 CONTIGUOUS PORTIONS METHOD

The contiguous portions method is outlined in HS(G)49. It involves measuring the detector response to a calibration source placed beneath the monitor in adjacent, but not overlapping, positions until the whole detector area has been covered (see Figure 1). The responses are then summed together and background corrected to give the overall response expected from one calibration source of area equal to the total covered by the individual source positions.

The semi-infinite-plane efficiency is then determined by comparing the summed response to the product of the surface emission rate per unit area of the calibration source and the number of calibration positions employed. This may be expressed algebraically as follows:

$$EFF = \frac{\sum_{i=1}^n (R_i - B)}{n.SER} \quad (1)$$

where EFF is the efficiency in counts per second per unit area (cps per emission per cm²)

R_i is the detector response at source position i (cps)

B is the background (cps)

n is the number of source positions

SER is the surface emission rate per unit area (s⁻¹.cm⁻²)

It is important to recognise that the efficiency will depend on such factors as the decay characteristics of the radionuclide being used and the distance between the detector and the calibration source.

1.3 PROJECT PLAN

The approach taken to this project involved identifying potential sources of uncertainty within the contiguous portions method and conducting a series of experiments in order to quantify them. The direction taken at each stage of these investigations was dependent upon

the findings of studies at the previous stage. The general format of the project was as follows:

identification of factors which would possibly affect the results of a contiguous portions calibration

selection of instruments and sources (representative of those commonly used) to investigate the factors identified above

1

experimental determination of effects on detector response due to:

- detector uniformity
- source uniformity
- source - detector separation
- radiation type and energy
- backscattering
- source edge effects

development of a draft protocol for field studies of the contiguous portions method

comprehensive field studies at five laboratories

evaluation of experimental data and field studies

practical validation of the contiguous portions method using a very large area source

production of final protocol and accompanying guidance

2 EQUIPMENT

The monitoring equipment employed during this project is detailed in Table 1 along with the abbreviated forms of their names which have been used throughout the remainder of this report. The BP7, DP2, G2 and GP13 probes were used in conjunction with the Electra Ratemeter operated in 'Integrate' mode to provide the mean count-rate observed during a ten second period.

Table 2 lists the radioactive sources used, their dimensions and where appropriate any ISO filters^[5] that were attached. The 'point' sources consisted of a drop of radioactive solution dispensed to the centre of an aluminium substrate (20 x 20 x 3 mm). The sources were then covered with either an appropriate permanent filter (as stipulated in ISO 8769-2 to attenuate any radiations that were not required), or with a thin VYNS film to seal in the activity when filters were not necessary.

The large area sources (100 x 100 mm) were manufactured without rims (ie, their activity extends to the edges of the sources) on 3 mm thick aluminium backing plates. Where filters were required, they were supplied independently and could be placed over the source as desired.

The 500 x 500 mm source (¹³⁷Cs) was prepared at NPL by dispensing known amounts of radioactive solution on to a sheet of aluminium foil. The foil was marked into 10 x 10 mm areas and drops of active solution dispensed sequentially into each area. The foil was then attached to an aluminium substrate of 3 mm thickness, in accordance with ISO 8769-2. The active surface was subsequently covered with a further thin layer of aluminised Mylar. This was required to protect the active surface and to prevent contamination of the 500 x 500 x 1 mm stainless steel filter.

Further equipment included 100 x 100 x 3 mm plates of aluminium used to provide additional backing for the large area sources and strips of aluminium (100 x 10 x 3 mm and 100 x 5 x 3 mm) for use around the large area sources to simulate rimmed calibration sources. A set of attenuating masks was employed to determine the uniformity of the α - and β -emitting sources by exposing different areas of each source to a large area windowed proportional counter. For the homogeneity testing of the photon sources, a lead collimator with an entry diameter of 25 mm was employed.

3 EXPERIMENTAL INVESTIGATIONS

3.1 DETECTOR PROFILES

The response of a detector to a radioactive source is highly dependent upon the nature of the radiation being measured. With photon emitting sources, it is possible for photons to enter the probe through the sides of the outer casing and be successfully counted; however this effect is not observed with α -particles as they are completely attenuated in the casing material. Similarly, the distance at which the monitor is positioned from the surface of the source is important; the variation of the detector response with source - detector separation at short distances is more pronounced for alpha emitters due to their short range.

To examine the effects of these features on the contiguous portions method and to quantify any contribution they make to a calibration uncertainty, the variation in the response of a range of monitors to the positioning of point sources of various radionuclides relative to them was studied. Detector profiles were performed for the probe - nuclide combinations and probe orientations detailed in Table 3. Diagrammatic representations of the probe orientations used can be found in Figures 2 to 5 for EP15, DP2, GP13 and G2 probes respectively.

A sheet of clear acetate was marked with a 1 cm grid and fixed to a workbench. The monitor under investigation was clamped at a known height above a designated origin on the grid and a spirit level employed to ensure that it was horizontal.

A point source was positioned at the origin and the detector response recorded; a minimum of three measurements were made and their mean value determined. The source was then moved out from the origin at regular intervals (usually 0.5 or 1 cm) and the measurements repeated. The distance from the origin at which no further measurements were necessary was reached when the detector response equalled the background count-rate. The source was then returned to the origin and measurements performed in the opposite (negative) direction. The procedure was repeated for a number of source - detector distances depending upon the nature of the radionuclide being measured.

Additional sets of measurements were made for the α - γ emitting sources (^{234}U and ^{241}Am), with a sheet of paper placed over the source to attenuate the α -particles. This allowed the response to the α -particles alone to be calculated by subtraction of the γ response (measured with paper over the source) from the α + γ response (with no paper).

When additional detector profiles were performed for the same probe - nuclide combination but with the probe in a diagonal orientation, measurements were only made at a source - detector separation of 1 cm.

3.2 UNIFORMITY OF SOURCES

The uniformity of reference sources is defined in ISO 8769-1 and ISO 8769-2 as '... the estimated standard deviation of measurements of the individual portions about the mean value for the whole surface expressed as a percent of the mean value ...' where the portions

of the source measured are equal in area and not greater than 10 cm². It is required that the uniformity of such sources in terms of surface emission rate is better than $\pm 10\%$.

The homogeneity of the α - and β -emitting large area reference sources employed in this project were tested using a windowed proportional counter and a set of attenuating masks of sufficient thickness to absorb particles of the maximum energy emitted. The proportional counter was exposed consecutively to nine areas of each source and the emission rates recorded. The mean value for each source was determined and the results for the individual areas expressed as a percentage deviation from the mean emission rate obtained for that source. The standard deviation of the detector responses from the mean value was then calculated to indicate the homogeneity.

The large area photon sources were characterised using the G2 probe and a lead collimator. The detector responses to sixteen areas of the sources were obtained and analysed as above to determine the standard deviation from the mean value.

3.3 BACKSCATTER

The backing plates of large area reference sources should be of sufficient thickness '... to prevent emission of the particulate radiation through the back of the source ...' and such that the '... addition of further such material would not increase the quantity of emitted particulate radiation resulting from back-scattering ...' [4, 5].

The reference sources for this project were constructed with permanent 3 mm thick backing plates in compliance with the requirements of ISO 8769-1 and ISO 8769-2. The effect of backing plate thickness on the response observed from survey meters was investigated by systematically increasing the plate thickness beneath a source, whilst maintaining a constant source - detector separation, and noting any resulting changes in detector response.

An appropriate monitor was positioned centrally over each of the large area sources in contact with the surface. Three measurements of detector response were made and their mean value calculated. A further backing plate, also of 3 mm thickness, was then placed beneath the source and a similar set of measurements made. This process was repeated for the addition of two further backing plates (a total of 12 mm of backing material) and for each of the monitor - nuclide combinations at source - detector separations of 0, 3 and 10 mm.

The photon sources used were fitted with removable filters to absorb their particulate radiation emissions. The source - detector separations adopted in this investigation were taken to be between the active layer of the source (below the filter) and the detector window of the monitor.

3.4 EDGE EFFECTS

At the edge of the active layer of a radioactive source, there will be some radiation emerging that will experience less attenuation than radiations emerging at a similar angle from the main body of the source (see Figure 6). For a source of semi-infinite geometry, this effect will

not be observed by a detector as the source edge will be far from, and facing away from, the sensitive volume of the detector.

For the contiguous portions method, sources of such semi-infinite geometry are not required and a source of finite area is moved around beneath the detector. By the nature of the contiguous portions method, the detector is repeatedly exposed to the source edges. Therefore, any effect that the edges of a source may have upon detector response will be magnified according to the number of measurement positions used during the calibration.

To study this and to determine any effects it has on the contiguous portions technique, an inactive plate of the same dimensions and material as the source backing plates was placed adjacent to a source to mimic the attenuation of radiations emitted from the centre of the source. A series of measurements were performed to compare detector responses at the edge of the source with and without the inactive plate in position.

With the centre of the detector area positioned over the edge of the source (Figure 7), the detector response was recorded (a minimum of 3 times each). The inactive plate was then positioned against the edge under study and the measurements repeated for comparison with the results above. This series of measurements was made at source - detector separations of 0, 3 and 10 mm for each source - detector combination.

3.4.1 Rimmed Sources

Commercial reference sources are usually supplied with a rim for increased radiation protection in handling the sources and to guard the surface of the source against accidental damage. Since the large area sources used during this project were rimless, ie, the active area extended to the edges of the backing plate, some consideration had to be given to the possible differences in detector responses obtained from rimmed and rimless sources.

To simulate rimmed calibration sources where the backing plate extends beyond the active area, additional measurements were made for ^{57}Co with the EP15 probe with strips of aluminium placed around the source (see Figure 8). This source - detector combination was chosen since the detector window was one of the smallest of the detectors used and would present the largest variation resulting from this effect. Data was obtained for both 5 mm and 10 mm wide rims at source - detector heights of 0, 3 and 10 mm.

3.5 FIELD TRIALS

In order to test the contiguous portions technique, a field study was organised in which five laboratories performed measurements in accordance with a draft protocol (example pages of this draft protocol are included in Appendix II). Five probes (DP2, EP15, BP7, GP13 and G2) and six large area sources (^{241}Am , ^{234}U , ^{14}C , $^{90}\text{Sr}/^{90}\text{Y}$, ^{57}Co and ^{137}Cs), were circulated around the laboratories and appropriate detector - nuclide combinations studied. The BP7 probe was used in conjunction with ^{14}C in the field trials; a detector profile was not performed for this source - detector combination.

Check sources were provided so that the monitors could be tested before use and any damage during transportation identified. The optimum operating voltages for the probes (applicable for the DP2 and G2) were determined in advance from plateaux to ensure that no additional uncertainty would be introduced due to the laboratories adopting different voltages. A template was supplied which indicated the detector area and the positions in which a 100 x 100 mm large area calibration source was to be measured. This aimed to reduce variations in the results due to source and monitor positioning errors.

Measurements were made with the sources in various orientations according to the uniformity of each source to provide results for: a 'normal' situation (avoiding areas of the source which displayed significant deviation from the mean emission rate observed during uniformity testing); a 'high' case scenario (where areas of the source with the highest emission rates were specifically targeted) and a 'low' case scenario (in which the areas of lowest emission rate were used). The purpose of measurements in such varied orientations was to indicate the range of final results that could reasonably be achieved by performing measurements in 'random' source orientations and disregarding the uniformity.

For the smaller probes included in the field trials (EP15, DP2, BP7 and G2), it was also possible to determine 'centre' values with the source positioned centrally beneath the detector. Since the source was larger than the detector area for those measurements, the monitors could be calibrated in accordance with the general method in HS(G)49 and the results could be compared directly with those obtained using the contiguous portions technique and contribute to the validation of the method.

Standardised reporting sheets were issued for each detector - source combination and each source orientation to be studied (see Appendix II).

3.6 VALIDATION OF THE CONTIGUOUS PORTIONS METHOD

A direct comparison between the contiguous portions method and the usual procedures laid out in HS(G)49 for the calibration of radiation monitors when a source of greater active area than the detector is available, was made by the preparation of a very large area source.

A known activity of ^{137}Cs was dispensed onto a 500 x 500 mm piece of aluminium foil marked with a 10 mm grid. Once the solution had dried, a thin layer of aluminised Mylar was fixed to the surface to seal in the activity. For this very large area source to comply with the requirements of ISO 8769-2 for photon sources, an aluminium backing plate (3 mm thickness) was placed beneath the foil and a stainless steel filter (1 mm thickness) was placed over the Mylar to attenuate the beta emissions.

The GP13 probe was positioned at a height of 3 mm, centrally above the source. Three 30 second measurements were performed and their mean count-rate determined. The source was then rotated through 90° and three further measurements made. This process was repeated until all four orientations of the source had been studied; the overall mean count-rate was then calculated.

Once measurements were complete, the backing plate and filter were removed from the source. The foil and mylar were then cut into twenty-five 100 x 100 mm pieces and mounted upon aluminium backing plates (again 3 mm thickness) and covered with stainless steel filters (1 mm thickness) of the same dimensions.

A perspex jig was manufactured to reproducibly mount each piece of the source (with their backing plates and filters), in turn 3 mm below the probe. Measurements of each of the individual pieces were then made and the detector responses to them were recorded. Calculation of the deviation of each square from the mean count-rate of all 25 allowed a representative piece of the source to be chosen for detailed experimentation with the contiguous portions method.

A grid containing twenty-five adjacent but not overlapping 100 x 100 mm squares was accurately drawn up. With the representative 100 x 100 mm piece of the very large area source positioned in the central square of the grid, the GP13 probe was fixed centrally and horizontally, at a distance of 3 mm above the source filter.

The source was then carefully removed from the grid, ensuring that the probe was not disturbed, and the background count-rate recorded. Detector responses were measured with the source in each of the 25 squares on the grid. To improve counting statistics and reduce the effect of any slight positional errors and source inhomogeneity, measurements were performed with the source in the four possible orientations (0°, 90°, 180° and 270°) within each square and their mean value determined.

After subtracting the mean background from each of the mean detector responses, the sum of the 25 results was compared with the mean count-rate (background corrected) observed for the very large area source (before it was cut up). This comparison allowed the basic principles of the Contiguous Portions method, summing together results from individual source measurements rather than measuring one large source, to be validated.

4 RESULTS AND DISCUSSIONS

4.1 DETECTOR PROFILES

The results of the detector profile investigations are contained in Tables 4 to 16. Corresponding graphs of these data can be found in Figures 9 to 21.

Alpha Emitters

The detector profiles obtained for the α -emitters (Figures 9 to 12), show an approximately square response for a source - detector separation of zero, as the point source is moved beneath the detector area. As would be expected, the count-rates observed fall dramatically once the source reaches the edge of the detector since the α -particles are unable to penetrate the outer casing of the probe. As the source - detector separation (height) is increased, the angle of incidence is improved and the fall off in the count-rates observed is less severe.

It is interesting to note the differences in the response characteristics for the two detectors (EP15 and DP2). The EP15 is a circular probe with a window radius of 2.9 cm. The data for ^{241}Am at a source - detector separation of zero, reflects this well with the response changing from maximum at the 2.5 cm horizontal position to almost zero at 3.0 cm. The ^{234}U data however shows a reduction in response occurring at a horizontal position somewhere between 1.5 and 2.0 cm. Since ^{234}U is a relatively low energy α -emitter (E_{max} of 4.8 MeV) compared with ^{241}Am (E_{max} of 5.5 MeV), this suggests that the entry window is non-uniform and is thicker at the extremities than at the centre. It highlights the need to be aware of the uniformity distribution of the source being used for calibration and of the window thickness. For the DP2 probe, this difference is not apparent, suggesting a relatively uniform detector window. The reductions for this probe occur between 3 and 4 cm corresponding to the window semi-width of 3.5 cm. On the other hand, whereas the EP15 showed little difference in response at source - detector separations of 0 and 1 cm, the DP2 shows an almost 50 % reduction in response between the same two separations, illustrating perhaps that the DP2 window is somewhat thicker than that of the EP15. This will make the DP2 more sensitive to spectral degradation of α -emitting sources.

Beta Emitters

The detector profile of $^{90}\text{Sr}/^{90}\text{Y}$ (Figure 13) clearly shows the greater range of the β -particles. When the source and detector are in contact with each other (H equal to 0 cm), the profile obtained is still approximately square. However at greater separations, a smoothing of the response is observed, exaggerating the effect of the angle of incidence described for α -particles.

Since the ^{14}C source and BP7 probe were only used for the field trials, a detector profile is not available.

4.1.3 Photon Emitters

The profiles obtained for the photon sources (Figures 14 to 21) reflect the detector dimensions generally but do not offer the same definition as the α and β sources, due to the long range of the γ -rays and their ability to penetrate the detector walls.

The asymmetry of the profile observed for ^{57}Co with the G2 probe at a height of 1 cm (Figure 20), is probably due to an error in repositioning the probe after adjusting its' height.

4.1.4 Cumulative Responses Against Horizontal Distance

The detector responses obtained for each detector - nuclide combination at a separation (height) of 1 cm, were plotted on graph paper emanating radially from the origin. Figure 22 is an example of such a plot for ^{234}U and the DP2 probe (when diagonal profiles were studied circular plots were made). From the plots, cumulative response curves were generated in the following manner.

The mean of the responses observed at each distance from the origin was multiplied by the area of the annulus enclosing those values, to obtain an estimate of the number of counts that would have been observed if measurements had been made with the source in all positions within that annulus. A running total of the estimated counts obtained as the source - detector distance increases radially, was calculated in order to determine the distance at which the radiation could no longer be detected. An estimation of the maximum number of counts that could be observed if measurements were continued to an infinite distance, was made from this running total data; this corresponds to the semi-infinite-plane response (Table 17 shows a typical calculation of the detector responses obtained for ^{234}U and the DP2 probe).

The detector responses were plotted as a percentage of the estimated semi-infinite-plane response so that the distance at which to cease further measurements could be determined easily (when a desired percentage of the maximum counts would be reached). The graphs obtained for all of the detector profiles have been included for comparison (Figures 23 to 31), that for the example of ^{234}U given above is Figure 26.

Most of the curves observed were 'smooth' s-shapes, with the response increasing rapidly from zero and then levelling off at greater distances. The response of the G2 probe to ^{137}Cs (Figure 31) contains a small 'blip'. This arises because the measurement interval (of horizontal distance), was increased at that point; since the count-rate observed at a particular distance was multiplied by the area enclosed by the annulus containing that position (the area being now substantially greater), a disproportionately large value resulted.

Table 18 summarises the minimum distances to which measurements should be made to ensure that the detector response obtained is at least 90 %, 95 % and 99 % of the maximum response possible. Although no hard and fast rules can be extracted from these data, general trends are visible.

For α -emitters, if the radial distance exceeds the detector window linear dimension by at least 0.5 cm, this is generally sufficient to ensure that 95 % of the total detector response has been studied. Where the detector profile is known, this knowledge allows a correction factor to be applied to contiguous portions data where measurements have been performed to this distance so that an estimate of the total response can be determined.

For β -emitters, the only data available is that for $^{90}\text{Sr}/^{90}\text{Y}$ but this is a high energy emitter ($E_{\beta \text{ max}}$ equivalent to 2.3 MeV) and will generally serve as a worst case example. For the DP2 detector, it is necessary to extend about 3 or 4 cm beyond the detector boundaries in order to achieve a 95 % cumulative response level. Clearly this figure will vary for other detectors depending on such factors as detector area, window material, source - detector separation, casing material and thickness. However, the data here suggest that this should not present any significant problems in applying the contiguous portions method.

For photon emitters, the situation is less optimistic. It would be expected that the 'required radial distance' would increase with photon energy. The G2 probe results confirm this but the GP13 results suggest the contrary. Nevertheless, the principal and significant indication is that the contiguous portions grid must be extended to very large distances beyond the detector boundaries in order to achieve even 90 % of the semi-infinite-plane response. The second and equally important conclusion that may be drawn is that for photon emitters, it is not evident that general 'rules of thumb' can be applied and, consequently, each detector needs to be profiled for a range of photon energies.

Generally, it is important not to overestimate the total response (by measuring to a greater distance than that for which a correction factor applies), as this will result in a misleadingly high detector efficiency. If that calibrated probe were then employed to assess a radioactive spillage, an underestimation of it's activity would be likely. This demonstrates the value of performing detector profiles for each source - detector combination.

4.2 SOURCE UNIFORMITIES

The homogeneity of the large area ^{241}Am , ^{57}Co and ^{137}Cs reference sources (detailed in Figures 32, 36 and 37 respectively), fully comply with the requirements of ISO 8769.

The uniformities observed for the large area sources of ^{234}U , $^{90}\text{Sr}/^{90}\text{Y}$ and ^{14}C (Figures 33, 34 and 35 respectively) demonstrated that the sources did not meet the requirements of ISO 8769-1. Nevertheless it was felt that it would be useful to use these sources to indicate potential sources of error; the field trial results illustrate these effects (see Section 4.5). It cannot be assumed that future users of this method will have sources of sufficiently better uniformity so that the effects of inhomogeneity can be neglected. Users of the contiguous portions method are therefore strongly advised to make measurements to ascertain the uniformity of a source before it is employed for the contiguous portions method, so that areas of significant deviation from the mean emission rate, can be avoided.

It is clear that any uncertainty due to source inhomogeneity can be reduced by rotating the source and making measurements in each orientation.

4.3 BACKSCATTER

The measurements performed to determine the effects of backscatter showed no significant change in detector response as the thickness of backing material was increased beneath the α -emitting large area sources; this is illustrated in Table 19 for ^{234}U .

Table 20 shows the data observed for $^{90}\text{Sr}/^{90}\text{Y}$ using the DP2 probe. For source - detector separations of 0 and 10 mm, there is clearly a small increase in detector response as the backing plate thickness is increased. The data obtained for 3 mm source - detector separation indicates that the detector response drops with additional backing material, however, the magnitude of that fall becomes less at the greater backing plate thicknesses. A possible explanation is that the measurements performed at a separation of 3 mm with a backing plate thickness of 3 mm, were flawed (perhaps due to a positioning error). If that result is discarded, the subsequent responses increase with additional backing material, following a similar trend to the data for the 0 and 10 mm source - detector separations. It is therefore reasonable to suggest that the addition of further backing material increases the response of the detector to β sources. However, it needs to be stated that the increase in response is relatively small compared with the pass/fail criteria that are required for monitors by HS(G)49.

The effects of increasing backing plate thickness beneath the ^{57}Co and ^{137}Cs large area photon sources can be found in Tables 21 and 22 respectively. Although the counting statistics are not sufficient to draw precise conclusions, it can be seen that the magnitude of the effect for ^{137}Cs is around twice that of ^{57}Co , implying that the effect increases with photon energy. At 12 mm backing, the effect for ^{137}Cs is of the order of 10 % and 5 % for ^{57}Co . There is also suggestion that the GP13 exhibits a larger effect than the G2 but the data is less precise here. It is significant too, that the backscatter effect does not appear to have maximised even at 12 mm backing; this is something which needs to be recognised when creating measurement protocols which allow comparison between calibration laboratories.

These results show that the effects of backscatter cannot be neglected for β - and γ -emitting calibration sources. The construction of the surface upon which the source is positioned during calibrations should also be considered as this may increase the effective backing material thickness (especially if the surface is metallic), and enhance the detector response accordingly. Although this effect is not unique to the contiguous portions method and contributes to calibrations performed using the traditional techniques, it should not be ignored.

4.4 EDGE EFFECTS

The results of the edge effects investigation (configuration shown in Figure 7), are detailed in Table 23 for each of the probe - source combinations used. The differences in count-rates observed before and after an inactive plate was positioned against the edge of each of the sources are not significant. For the majority of source - probe combinations and the various geometries studied, the values for the presence and absence of an abutted plate lie within the statistical uncertainties of each other at the 1σ level. Of the remaining data, only the ^{137}Cs source with the GP13 probe (in the short orientation), at a separation of 3 mm did not fall within 3σ of the individual results.

Rimmed Sources

The experiment in which 5 and 10 mm rims were placed around the edges of the ^{57}Co source (configuration shown in Figure 8), indicated that the presence of the rim does not change the count-rate observed over the edge of the active area; the results are contained in Table 24. The use of rimmed calibration sources in the contiguous portions method should therefore not affect any results obtained (providing the rim is taken into account when defining the source positions to be used).

4.5 FIELD TRIALS

The data obtained from the field trials is summarised in Tables 25 to 34. All results have been decayed to the same reference time to allow direct comparison. The mean, standard deviation and spread of the detector responses observed by each laboratory are also indicated.

Alpha Emitters

The field trials for ^{234}U showed good agreement (less than 2 % difference) between the mean values of measurements performed in the 'normal' and 'centre' configurations for both the EP15 and the DP2 probes at each of the laboratories (see Tables 26 and 28). It was expected that the least discrepancy would be observed for these probes as they have some of the smallest dimensions and therefore more closely approximate to the semi-infinite-plane response. When used in the conjunction with the α -emitting calibration sources, the horizontal distance required to achieve a semi-infinite-plane response is around 0.5 cm beyond the boundary of the detector area (see Section 4.1.4). For the measurements performed in the 'central' position, the source extended 1.5 cm beyond the DP2 detector and 2.1 cm beyond the EP15, suggesting that better agreement should be achieved with the EP15. However, the difference observed between the 'normal' and 'centre' arrangements was larger for the EP15 probe than for the DP2. This could be due to a combination of the EP15 having a less uniform detector window thickness than the DP2 (shown in the detector profiles), and the EP15 having an analogue logarithmic scale which is far more difficult to read accurately than the digital display of the Electra with the DP2 probe, especially at high count-rates. Also, the detector profiles obtained for ^{234}U with each probe suggest that the EP15 probe is slightly more sensitive to errors in the source - detector separation than the DP2 (see Figures 10 and 12).

For ^{241}Am , a higher energy alpha emitter than ^{234}U , agreement in the order of 5 % was achieved between the 'normal' and 'centre' configurations using the DP2 probe with a spread of around 5 % between the reported results of the laboratories. For the EP15 probe with ^{241}Am , the results were significantly worse (19 % spread in results between the laboratories and 16 % difference in the mean 'normal' and 'centre' values). These observations support the comments made above regarding the uniformity of the EP15 window and its' logarithmic scale. Although the detector profiles indicate that the DP2 probe is significantly more susceptible to height positioning errors than the EP15, this effect has not been observed (see Figures 9 and 11).

A clear improvement in terms of spread and standard deviation can be seen in the results for ^{241}Am with the DP2 when compared with ^{234}U and the DP2. This is most likely due to the significantly better uniformity of the ^{241}Am large area source, its' higher α -energy and the higher count-rate observed resulting in better counting statistics. When comparing ^{241}Am and ^{234}U using the EP15 probe, no distinct change can be seen. The effects described above for the DP2 are possibly being masked by problems with the analogue scale and detector window non-uniformity of the EP15.

The variation in detector responses that can be attained using a particular source - detector combination in different orientations, is indicated by the differences in the 'high' and 'low' case measurements for each field trial. The variations observed ($\sim 10\%$ for ^{241}Am and up to 45% for ^{234}U), clearly reflect the uniformity of those sources and highlight the need for awareness of source homogeneity.

4.5.2 Beta Emitters

The field trial of ^{14}C with the BP7 produced an agreement of better than 5% in the mean values obtained by the laboratories for the 'normal' and 'centre' configurations (see Table 30). The corresponding value for $^{90}\text{Sr}/^{90}\text{Y}$ and the DP2 was around 8% (see Table 29).

Although there is no detector profile for ^{14}C with the BP7, it is clear from the $^{90}\text{Sr}/^{90}\text{Y}$ profile data that significantly greater horizontal distances are necessary to achieve a semi-infinite-plane response for β -emitting sources than were required for α sources (see Table 18). This is evident in the field trial data upon comparison of the ^{241}Am and DP2 results with the $^{90}\text{Sr}/^{90}\text{Y}$ and DP2 values - the spread and standard deviation of the detector responses determined by each laboratory are consistently smaller for ^{241}Am where a closer approximation to semi-infinite response was achieved for the 'centre' measurement.

It is also plain from comparison of the ^{14}C and $^{90}\text{Sr}/^{90}\text{Y}$ data that increasing $E_{\beta \text{ max}}$ does increase the spread of results obtained, as would be anticipated, and hence there is scope for greater uncertainty in calibrations at higher energies.

4.5.3 Photon Emitters

When the field trial results were compared, it became clear that those from laboratory 2 generally seemed disparate from those of the other participants. For ^{137}Cs , the laboratory 2 responses were between 13 to 24% higher than the mean responses from the other laboratories; for ^{57}Co the differences were less pronounced. Subsequent discussions elicited the fact that laboratory 2 had conducted its measurements on a metallic bench, whilst wooden surfaces had been used elsewhere. The backscatter results reported in Section 4.3 indicate that the difference in substrates would explain the laboratory 2 results. In respect of this, although all results have been reported, the conclusions drawn about the field trials are based on the mean of the results with laboratory 2 excluded.

The 'centre' measurements performed in the field trials correspond to a calibration with the detector positioned centrally over the source; the 'normal' situation is where the detector is exposed consecutively to four different source positions as in a contiguous portions

calibration. 'Centre' position measurements were not possible for the GP13 probe as its dimensions exceed those of the source. However, the G2 probe (58 mm diameter) is much smaller than the large area calibration sources (100 x 100 mm), and 'centre' position measurements could be made.

Comparison of the 'normal' and 'centre' values for the G2 with each of the ^{57}Co and ^{137}Cs large area sources, clearly illustrates the problems central to the contiguous portions method. Tables 33 and 34 show that the 'centre' response obtained for the G2 is about 50 % less than that obtained in the 'normal' configuration. The central configuration is therefore not sufficient for observation of the semi-infinite-plane response and performance of a single central measurement is inadequate for calibrations by conventional methods involving photon sources.

It was shown in the detector profiles for ^{57}Co and ^{137}Cs with the G2 probe that the horizontal distance from the centre of the detector required to simulate even 95 % of the semi-infinite-plane response is 20 cm for ^{57}Co (a lower energy photon emitter), and in excess of 30 cm for ^{137}Cs (see Figures 20 and 21, and Table 18). For the horizontal distance of 10 cm used in the measurements for the 'normal' configuration, the detector profiles indicate that only around 65 % of the semi-infinite-plane response was achieved in the case of ^{57}Co with the G2 probe and around 45 % for ^{137}Cs (see Figures 30 and 31). Even though the measurements made were not sufficient for a contiguous portions calibration of the G2 probe, they were more than adequate to illustrate the extent of this problem.

The probe efficiency determined during a calibration is effectively the detector response to a source, divided by the surface emission rate per unit area of that source (see equation 1). Since the detector response of a probe has been shown to be underestimated when only a 'centre' calibration is performed, the probe efficiency is therefore also underestimated. If that probe was then employed in the assessment of a radioactive spillage over a finite area, an overestimation of its activity would result. While this raises concerns in terms of the accuracy and traceability of measurements, the overestimation of activity is preferable to an underestimation which could prove hazardous.

In the light of these findings, it is recommended that all monitors are calibrated for photon emitters via the contiguous portions method as only a fraction of the total detector response is obtained from a single central measurement. Operators should be aware of the backscattering capabilities of their work surfaces.

4.5.4 Repeatability of Contiguous Portions Measurements

The principal objectives of the field trials was to determine whether, using an agreed protocol, different calibration laboratories could produce comparable results for a contiguous portions calibration, without introducing any significant uncertainties in addition to those of a conventional 'centre' type calibration.

Examination of the field trial results in Tables 25 to 34 reveal that there are no significant differences in the standard deviations between the 'centre' and 'normal' cases. Indeed, for

Examination of the field trial results in Tables 25 to 34 reveal that there are no significant differences in the standard deviations between the 'centre' and 'normal' cases. Indeed, for the photon emitters on the G2 probe, there is even a suggestion that the standard deviations for the 'normal' case might be better than those for the 'centre' configuration. This might not be unreasonable. The rate of change of response with horizontal distance is greatest just beyond the probe dimensions (see Figures 20 and 21), and hence any asymmetry in positioning for the 'centre' measurement is likely to produce a larger standard deviation than for the extended contiguous portions measurements.

Overall, the conclusions must be made that different calibration laboratories should be able to operate a contiguous portions calibration and not introduce any additional uncertainty due to the laboratory itself. The recommended protocol for the use of the contiguous portions technique, revised in the light of the field trials, is presented in Appendix III.

4.6 VALIDATION OF CONTIGUOUS PORTIONS

The measurements performed on the very large area source (500 x 500 mm) while it was still intact are reported in Table 35. The background corrected response obtained was $314 \text{ s}^{-1} \pm 3 \text{ s}^{-1}$.

Figure 38 shows the detector responses obtained for each of the 25 pieces of the source once it had been cut up. Since square 7 showed the least deviation (0.18 %) from the mean count-rate of all 25 pieces, this square was chosen for measurements using the contiguous portions technique. A series of measurements were made with the square fixed in 25 different positions relative to the monitor (as indicated in the protocol). Table 36 provides an example of the measurements and the different source orientations used for the first source position.

The count-rates observed when the detector was exposed to the source in each of those 25 positions are detailed in Figure 39. When the count-rates are summed together and their uncertainties combined, an overall detector response of $319 \text{ s}^{-1} \pm 15 \text{ s}^{-1}$ results. This overall value compares well with that obtained for the very large area source and confirms the ability to simulate a very large area source using a smaller source in a number of positions. The uncertainty in the detector response derived using the contiguous portions method (~ 5 %) is, as expected, greater than that for the large area source (~ 1 %) due to the need for a larger number of measurements and the smaller individual net count-rates involved.

5 UNCERTAINTIES

5.1 MEASUREMENT UNCERTAINTIES

All uncertainties reported in this document are quoted at the 68 % confidence level (1σ), corresponding to a coverage factor of $k = 1$.

The uncertainties quoted for the backscatter and edge effects investigations were derived on the assumption of a rectangular distribution. The detector responses tabulated are the mean of three separate measurements made in each configuration. The standard uncertainty in the mean value was calculated using the following formula,

$$u = \frac{a}{2\sqrt{3}} \quad (2)$$

where a is the spread in the individual measurements

The standard deviations quoted for the field trials data were calculated according to NIS3003 ^[6] using the following equation,

$$s = \sqrt{\frac{1}{n-1} \sum (x_i - \bar{x})^2} \quad (3)$$

where s is the standard deviation

n is the number of measurements made

x_i is the individual measurement i

$\bar{x}$ is the mean value

The standard uncertainties quoted for the validation of the contiguous portions technique using the very large area source, assumed a Poisson distribution. Each measurement recorded during this experiment was the mean count-rate detected over a 30 second period using the GP13 probe and the Electra ratemeter.

The uncertainty in each measured count-rate is,

$$u_i = \frac{\sqrt{x \cdot t}}{t} \quad (4)$$

where x is the count-rate recorded (s^{-1})

t is the counting time (s)

The standard uncertainty given in the mean value of those measured count-rates is the standard deviation of the mean, s_m , given by,

$$s_m = \sqrt{\frac{1}{n(n-1)} \sum (x_i - \bar{x})^2} \quad (5)$$

5.2 UNCERTAINTIES IN THE CONTIGUOUS PORTIONS METHOD

Many of the uncertainties affecting contiguous portions calibrations are not unique to the method and would require consideration for calibrations performed according to conventional methods using only a 'centre' position measurement. Those factors include: source - detector separation; backscattering; detector uniformity and background count-rate.

Uncertainties in the dimensions of the active area, the shape of the active area and the homogeneity of the calibration source, are common to both methods but deserve some additional consideration for the contiguous portions method.

The only uncertainty contribution that is due solely to the adoption of contiguous portions, is that in source positioning.

5.2.1 Source Area

Detector efficiency is quantified in terms of counts per second per emission per unit area. The uncertainty in detector efficiency will therefore be dependent upon the uncertainty in the source area. If it is assumed that the dimensions of a typical 100 x 100 mm source will be accurate to within ± 0.5 mm, the uncertainty in its area is 1 %.

5.2.2 Source Corners

Commercially supplied calibration sources are often constructed of an active layer fixed onto a suitable backing material. The face dimensions of the backing material are usually greater than the active area to provide an inactive rim for safe handling. On rimmed calibration sources, it is not uncommon for the active layer to have rounded corners. Since the contiguous portions technique requires the source to be placed consecutively in adjacent but not overlapping positions, the inactive corners of the source will affect the detector response. Since drawing a source positioning grid to allow for the source corners would be very onerous, a contribution to the overall uncertainty can be made.

In order to estimate the uncertainty that these corners would introduce to the contiguous portions method, the radius of curvature on a typical reference source was measured. For a radius of curvature of 5 mm on a 100 x 100 mm source, 0.2 % of the nominal active area can be shown to be inactive and therefore not contributing to the detector response. A similar calculation for a 100 x 150 mm source indicated that the corners account for 0.15 % of the total area.

5.2.3 Source Uniformity

The uniformity of a calibration source is required by ISO 8769 to be within ± 10 % (a full definition is given in Section 3.2). It is possible for a source satisfying this condition to have two corners that deviate from the mean value by + 20 % and - 20 % respectively. Since contiguous portions involves exposing a detector to that source repeatedly, it is possible to

achieve greatly discrepant detector responses depending upon which corner of the source is most often apparent (as was shown in the field trials). A knowledge of the homogeneity of a calibration source can be used to define source orientations for each of the grid positions, that will avoid the most deviant areas of the source.

Source uniformity problems can generally be successfully minimised by rotating the source and making repeat measurements at each source position on the grid.

To estimate the maximum additional uncertainty that would result from randomly orientating a source during a contiguous portions calibration, a worst case scenario can be considered. For a detector of the same dimensions as an alpha-emitting calibration source, 100 x 100 mm, at least nine source positions will be necessary for a contiguous portions calibration (as in Figure 1). If the corner of the source showing 20 % greater than the mean value is deliberately placed closest to the detector, a detector response enhanced by 6 % will result. This scenario takes no account of the fact that the detector response rapidly falls off for alpha sources once the detector boundary has been exceeded, the figure of 6 % is therefore the maximum that could be observed.

5.2.4 Source Positioning

The additional uncertainty in the contiguous portions method due to source positioning errors are dramatically reduced by using a source positioning grid drawn up before making measurements (as suggested in the recommended protocol). Errors in the source positions within that grid will generally be randomised as each position in a large grid is studied.

If it is assumed that the source can be reasonably positioned to within 0.5 mm of the grid lines, a worst case positioning scenario can be determined. The detector profiles show that source positioning is most crucial for alpha sources, as the detector response is most sensitive to horizontal distance (see Section 4.1.1). The largest discrepancy in detector response would be obtained when the grid area not covered by a source, is maximised. This is achieved when the source is placed incorrectly a distance of 0.5 mm outwards from the central position, repeatedly for each source position surrounding the centre area as shown in Figure 40. This would result in a region of 2 % of the area of the source being left uncovered and hence maximum positioning uncertainty of 2 % for a 100 x 100 mm source.

6 CONCLUSIONS

The performance of detector profiles and source uniformity tests are vital to establish the number of source positions and orientations required before a contiguous portions calibration is undertaken.

For survey meter calibrations of photon emitting sources, detector profiles are necessary for a range of photon energies as proportionality of detector response cannot be assumed.

Detector responses are dependent upon the thickness of backing material beneath γ - and to a lesser extent β -emitting sources; the effects of backscatter must be considered and accounted for. The effects are negligible for α sources.

The repeated exposure of the detector to source edges during a contiguous portions calibration does not enhance the total detector response observed. Edge effects are not significant to the contiguous portions technique.

For calibration of monitors using photon sources, the contiguous portions method should be adopted, even when the probe dimensions are small.

The contiguous portions technique is a valid method for the calibration of large area survey meters using relatively small area sources.

Details of the extent of the measurement grid used in a contiguous portions calibration must be supplied. Provision of this information allows comparisons to be made with the results of previous years and also between calibration laboratories.

By far the largest contribution to the additional uncertainty in a contiguous portions calibration is the uniformity of the calibration source. A detailed knowledge of the uniformity distribution will allow a calibration configuration to be designed which will significantly reduce this.

The additional uncertainty in a calibration performed using the contiguous portions technique should not exceed 10 % if the guidelines enclosed are followed.

7 ACKNOWLEDGEMENTS

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Figure 1

The Contiguous Portions Technique

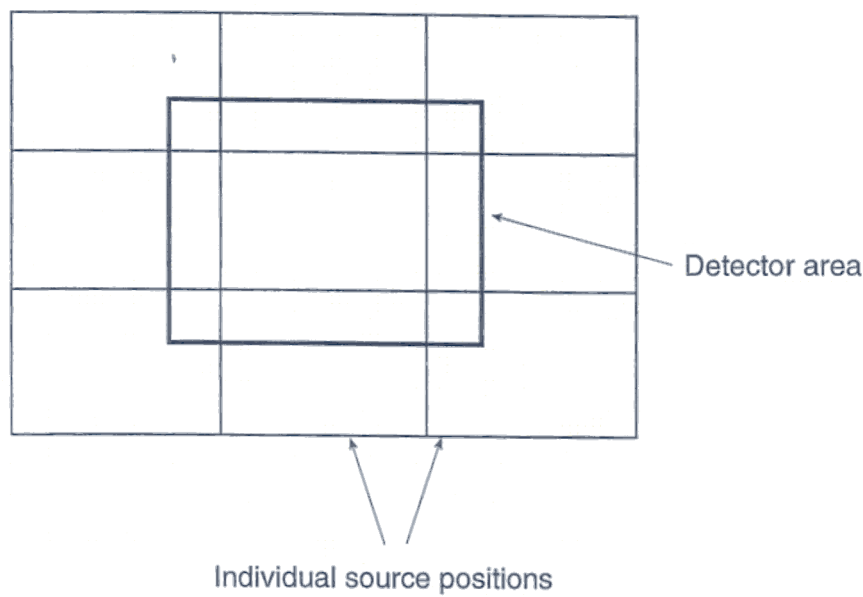


Figure 2

Normal Orientation for the EP15 Probe

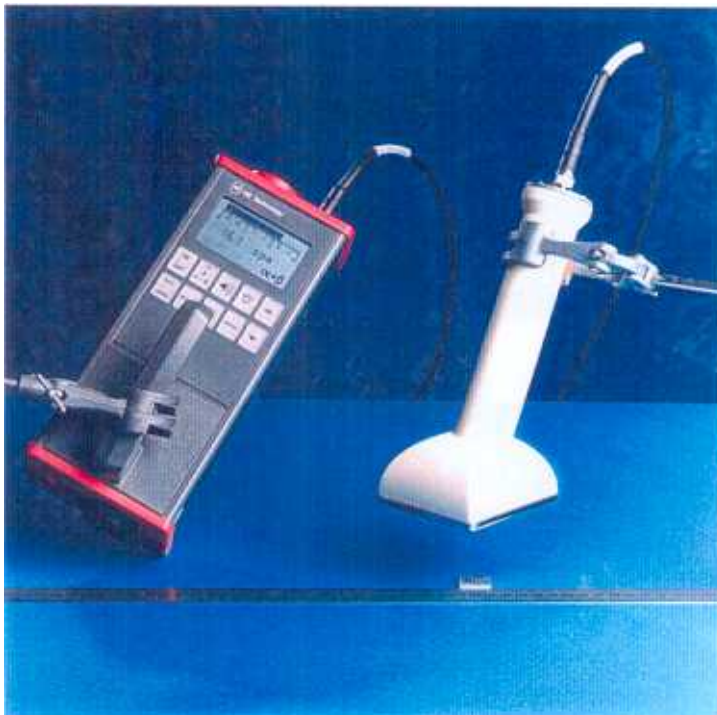


Figure 3

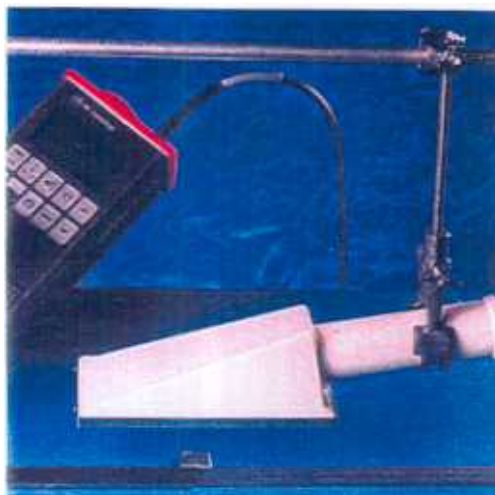
Probe Orientations for the DP2



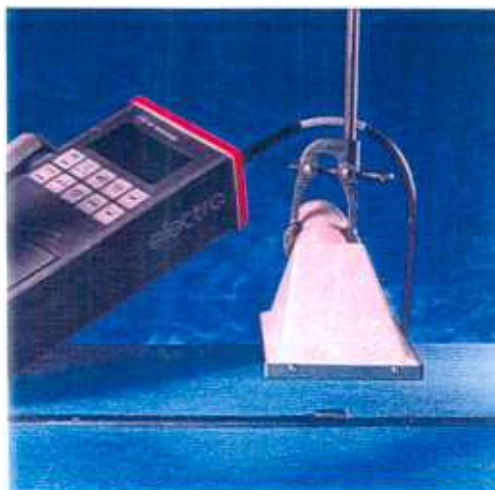
a) Normal Orientation



b) Diagonal Orientation

Figure 4**Probe Orientations for the GP13**

a) Long Orientation



b) Short Orientation



c) Diagonal Orientation

Figure 5

Normal Orientation for the G2 Probe

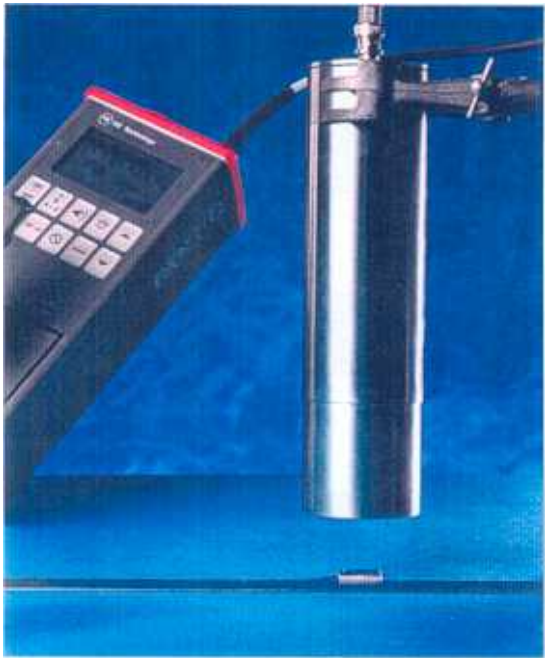
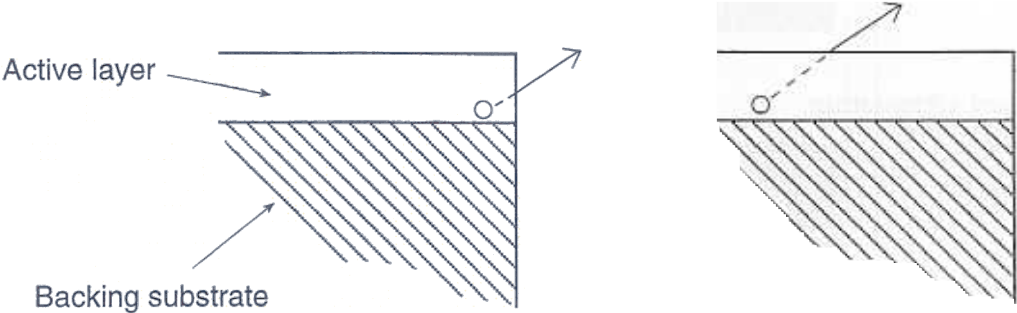


Figure 6

Attenuation Experienced by Radiations Emerging from the Edge and Centre of a Source



a) Path taken by radiation at edge of source

b) Path taken by radiation within the body of a source

Figure 7

Probe and Source Geometry for Determination of Edge Effects

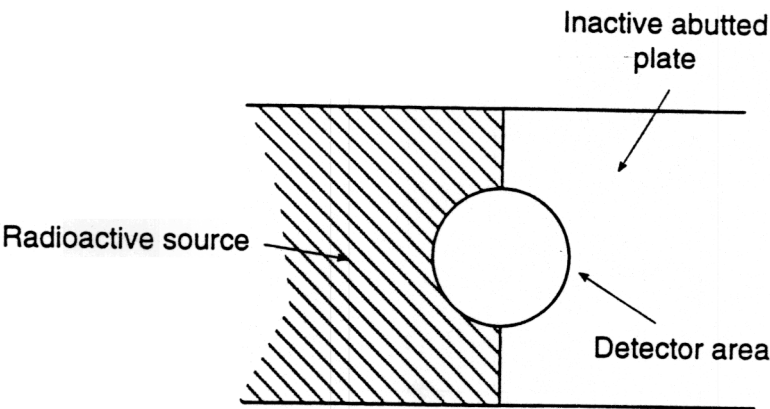


Figure 8

Simulation of a Rimmed Reference Source

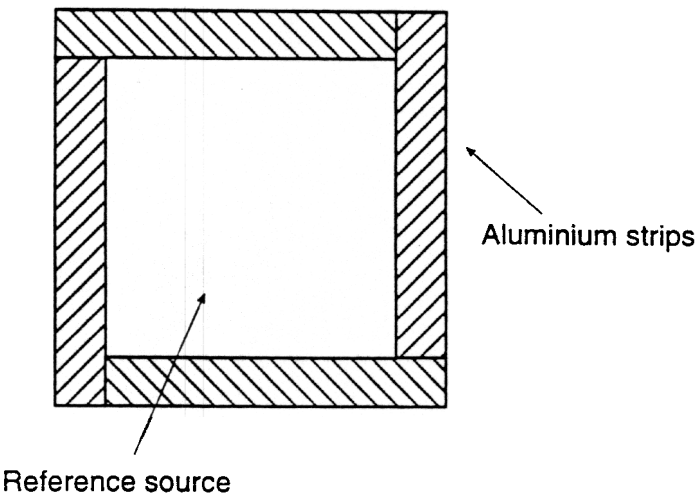


Figure 9

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation, Am-241 and EP15

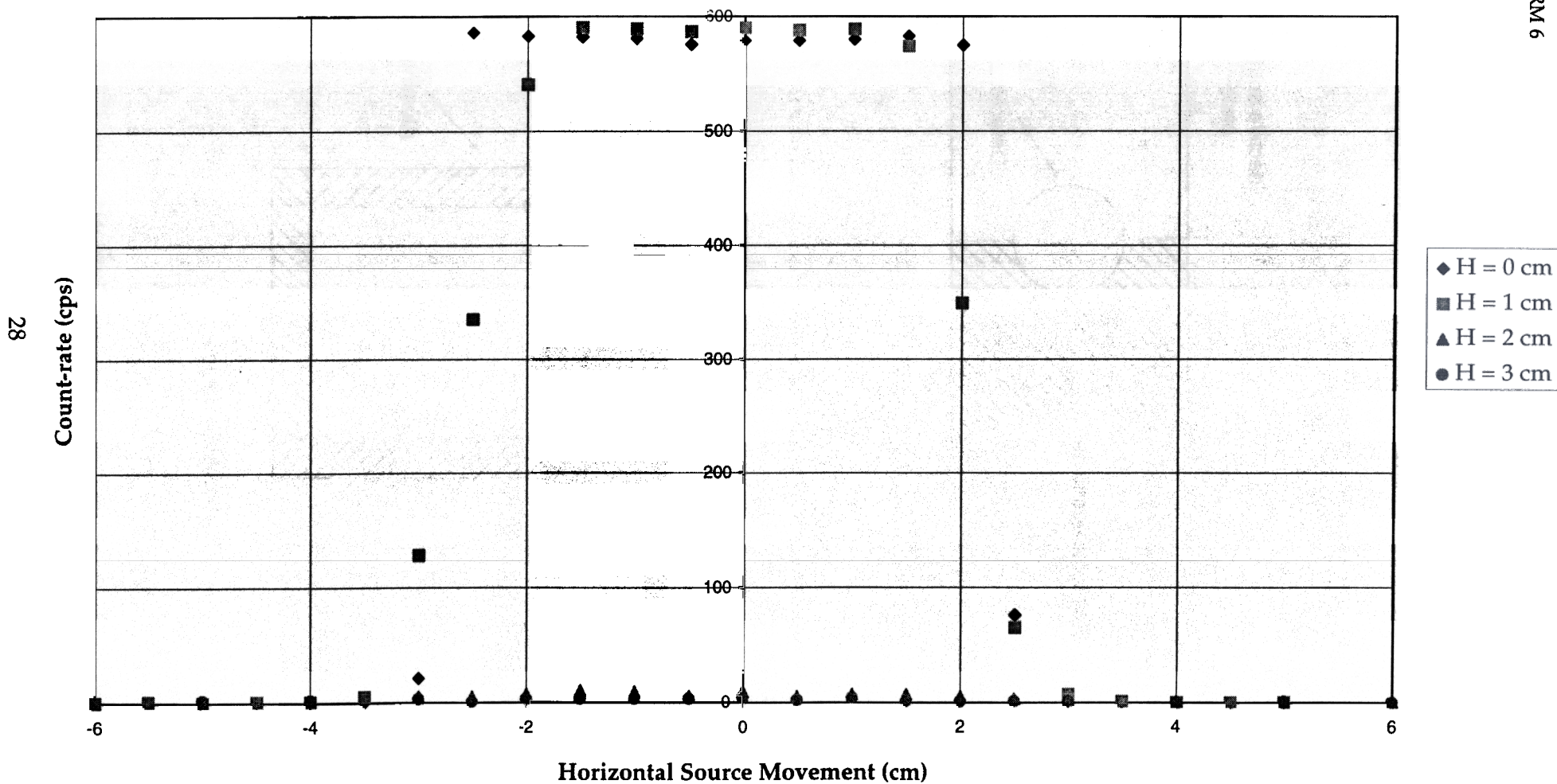


Figure 10

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation,
U-234 and EP15

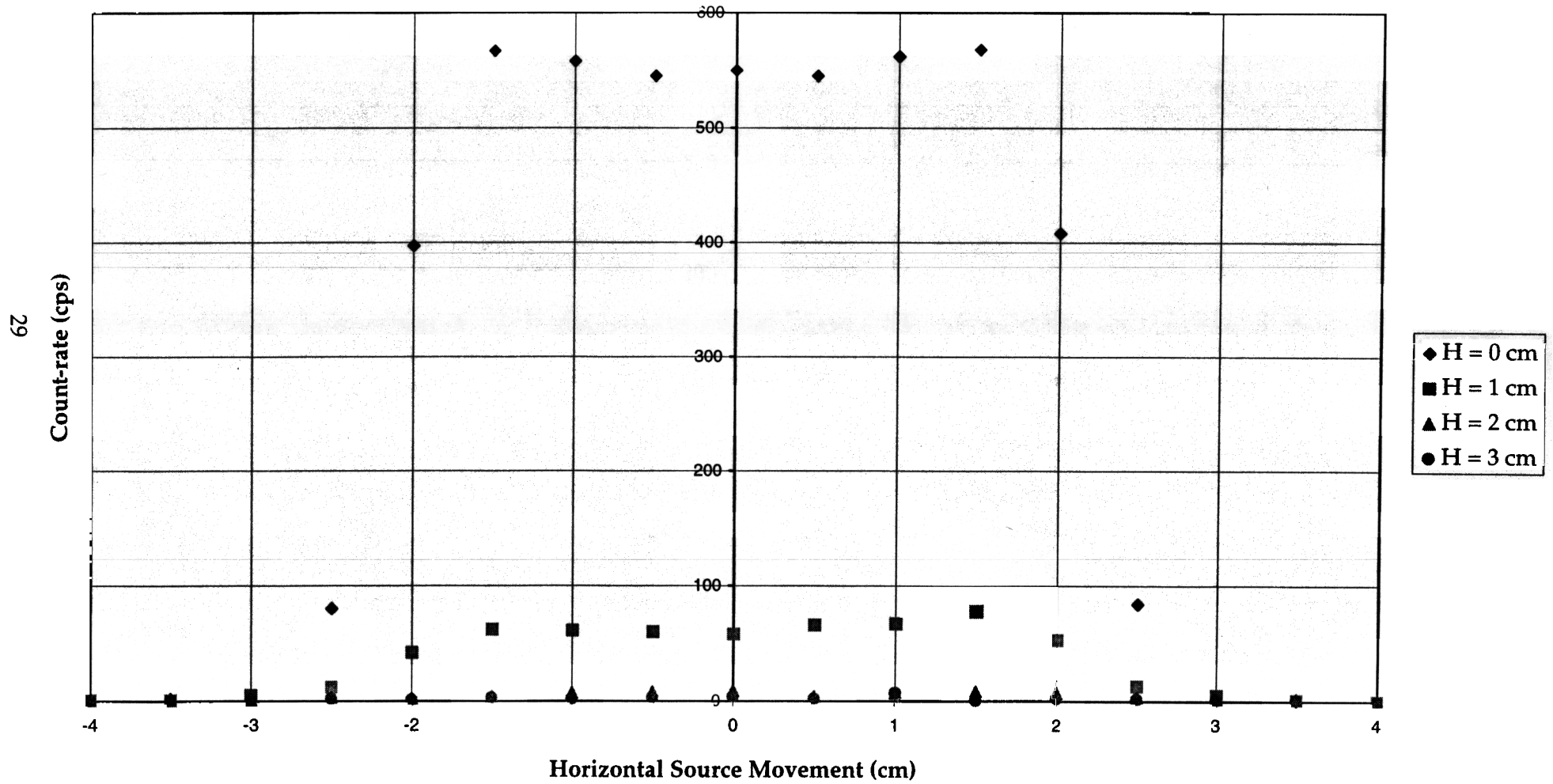


Figure 11

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation, Am-241 and DP2

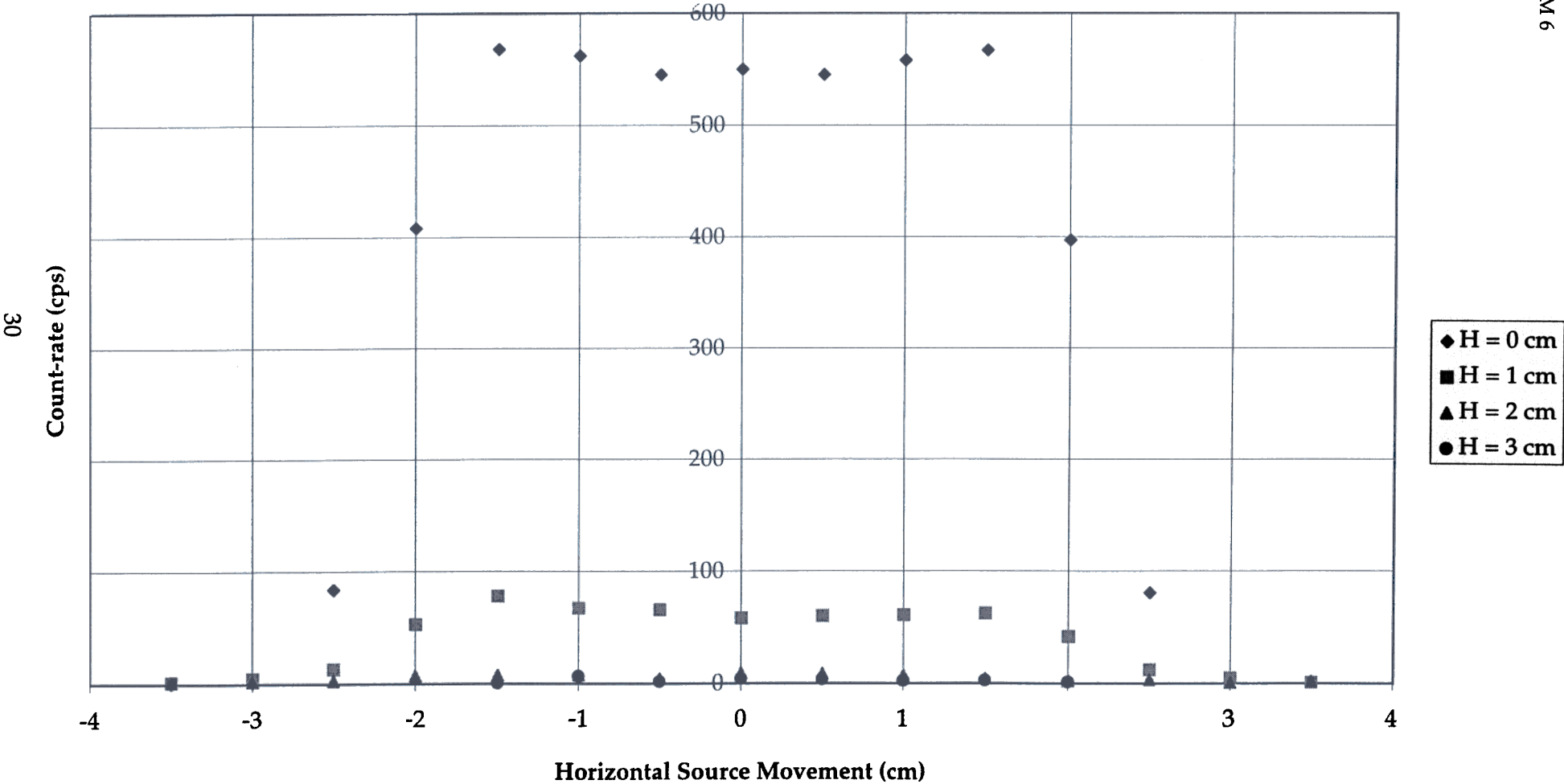


Figure 12

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation,
U-234 and DP2

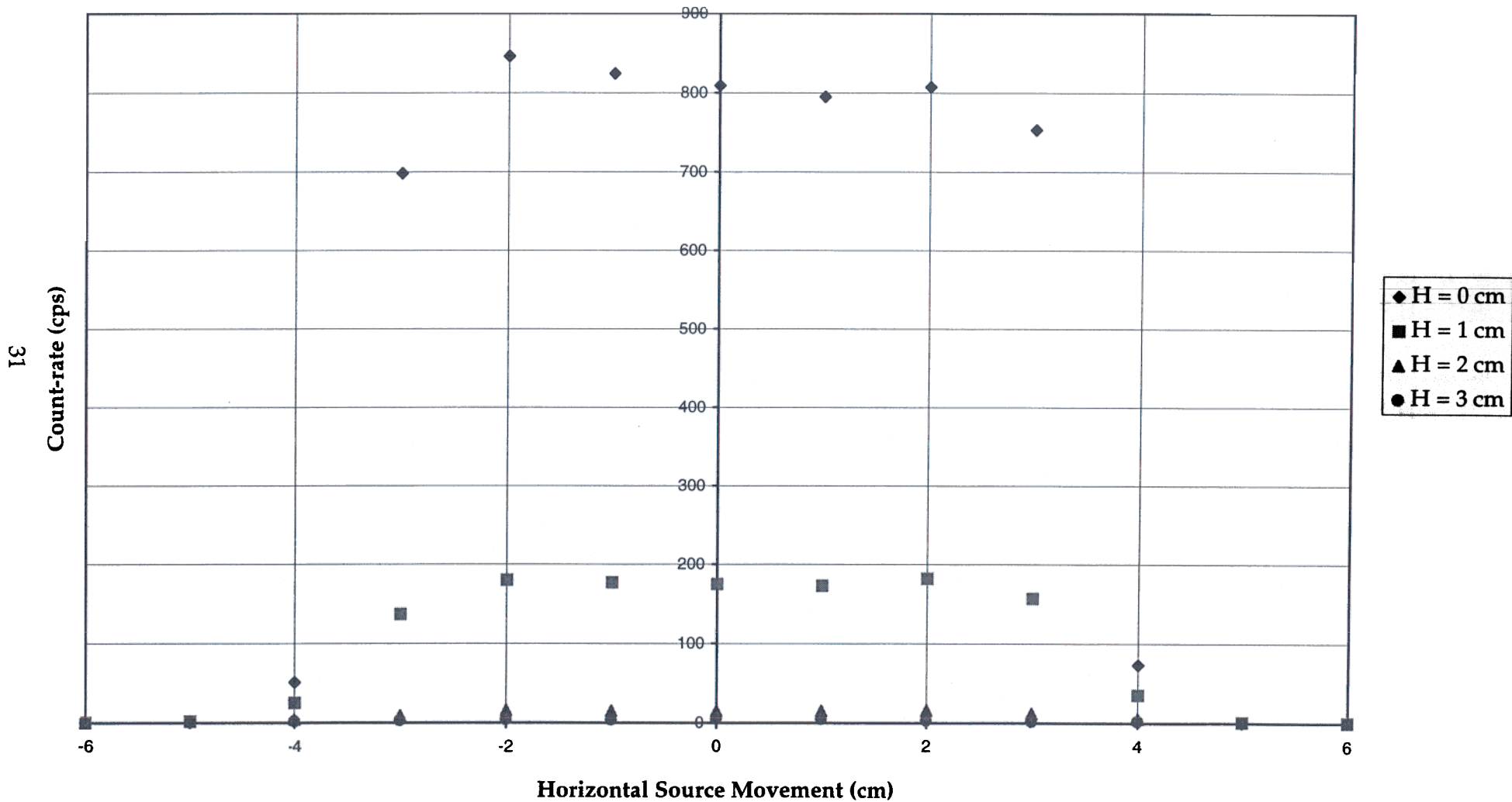


Figure 13

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation,
Sr-90 / Y-90 and DP2

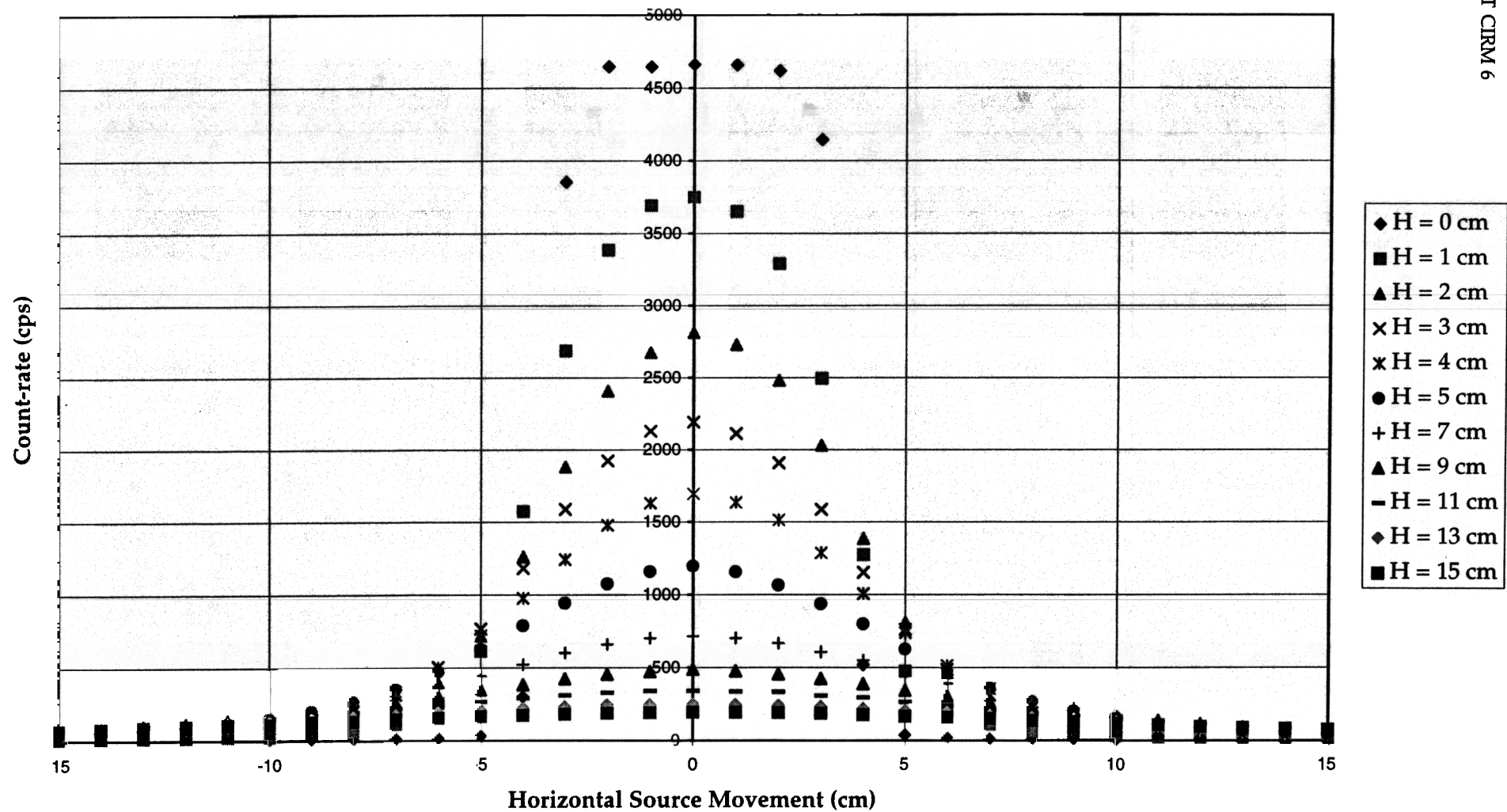


Figure 14

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation,
Sr-90 / Y-90 and DP2 (Diagonal direction)

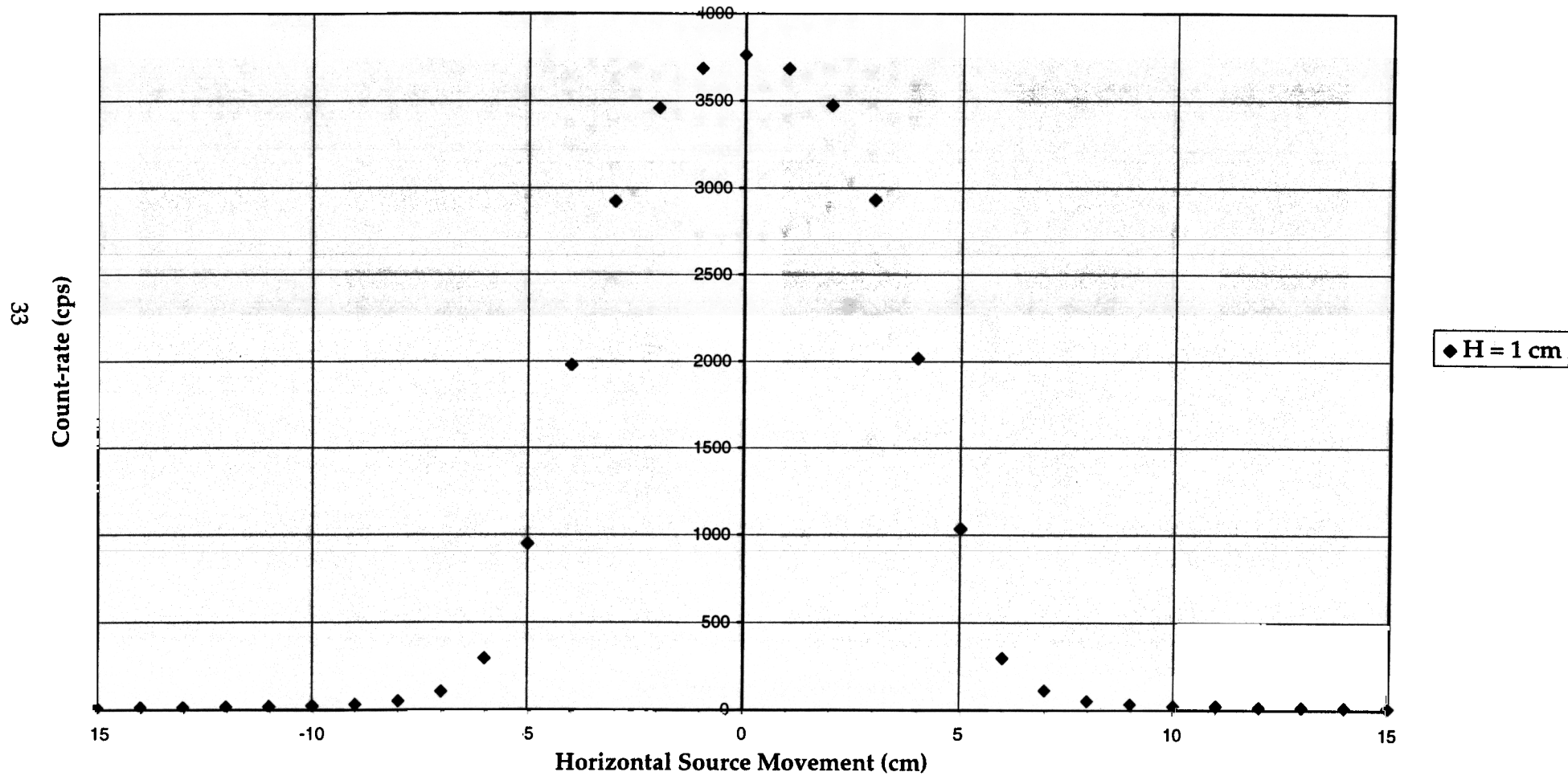


Figure 15

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation, Co-57 and GP13 (long orientation)

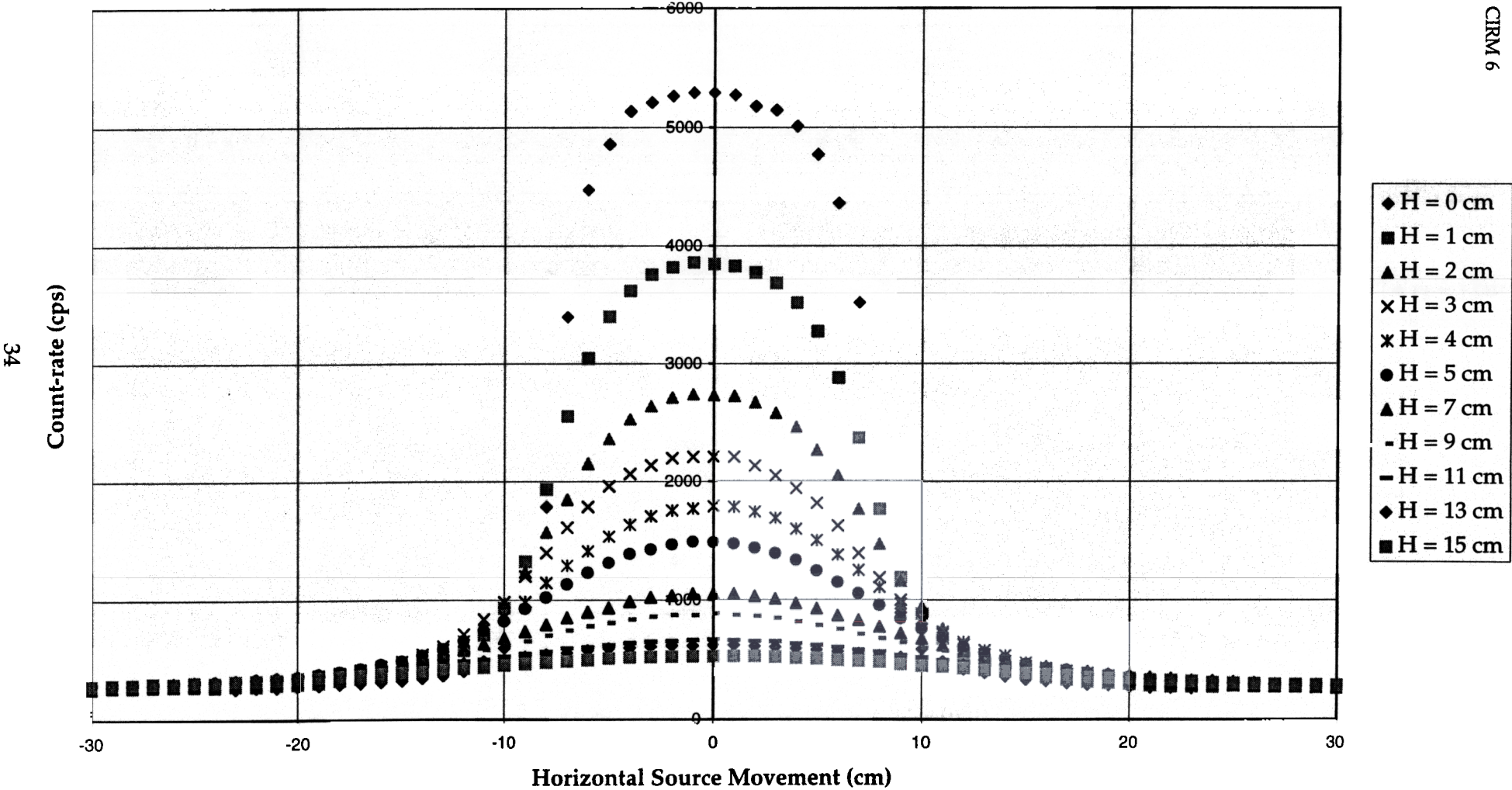


Figure 16

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation, Co-57 and GP13 (short orientation)

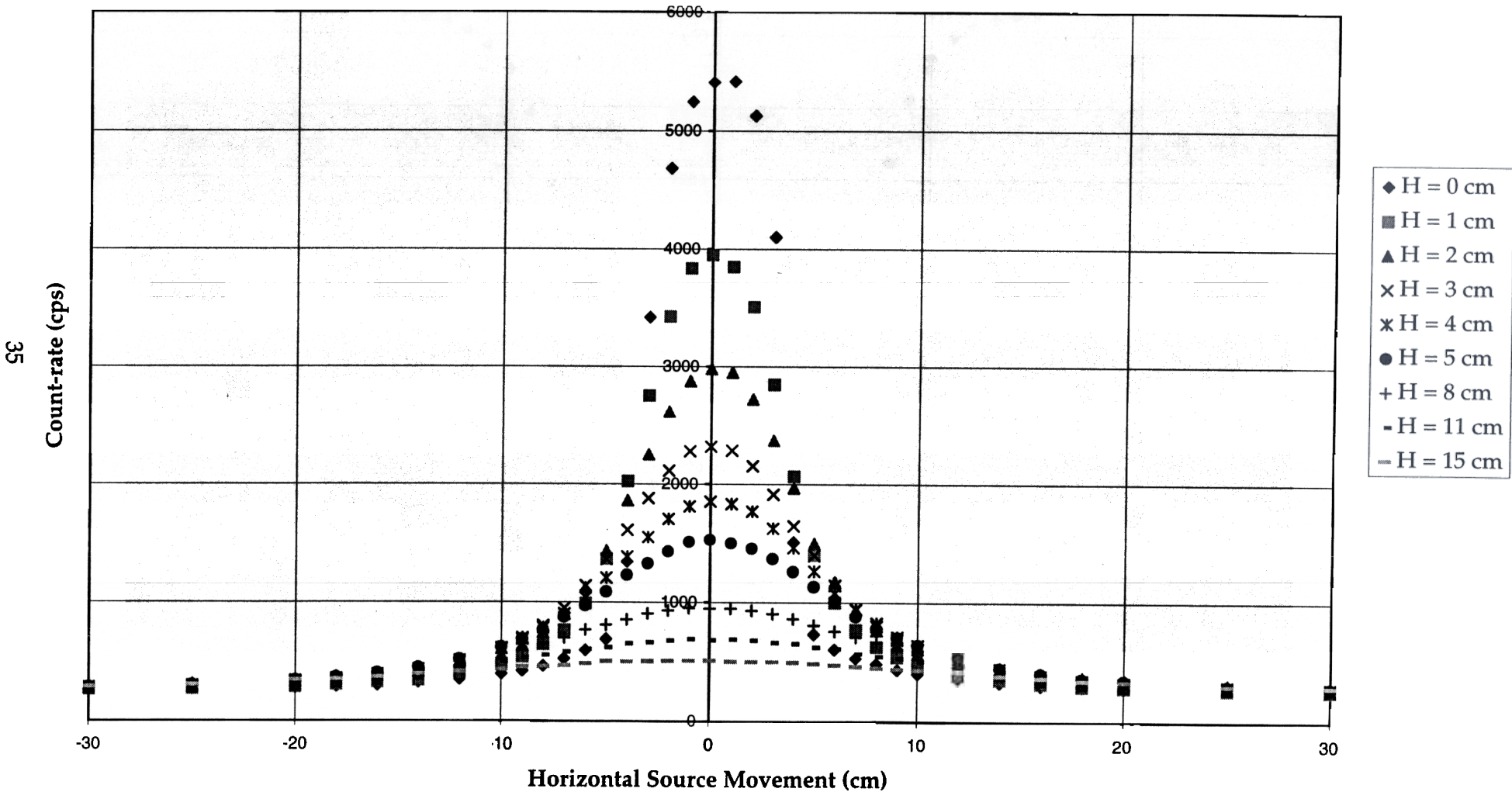


Figure 17

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation,
Co-57 and GP13 (Diagonal direction)

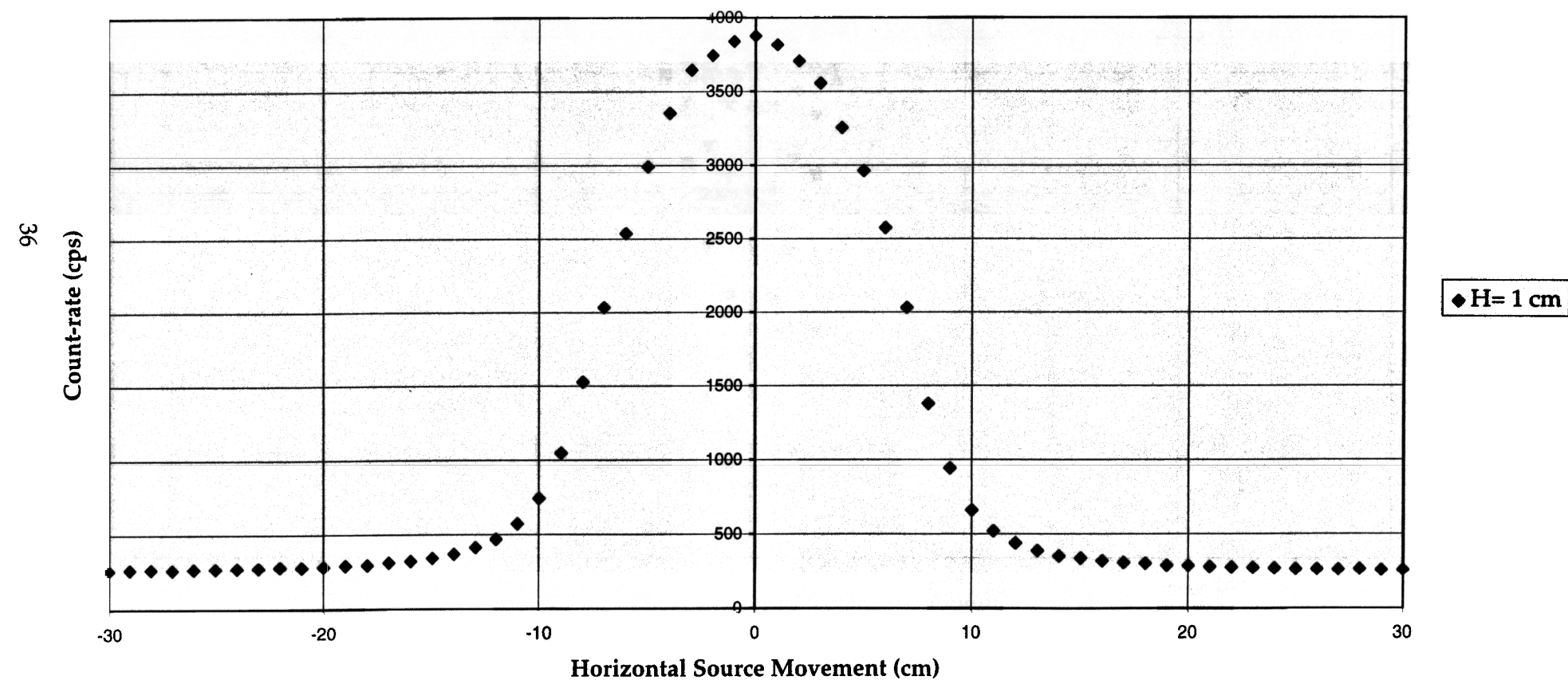


Figure 18

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation, Cs-137 and GP13 (long orientation)

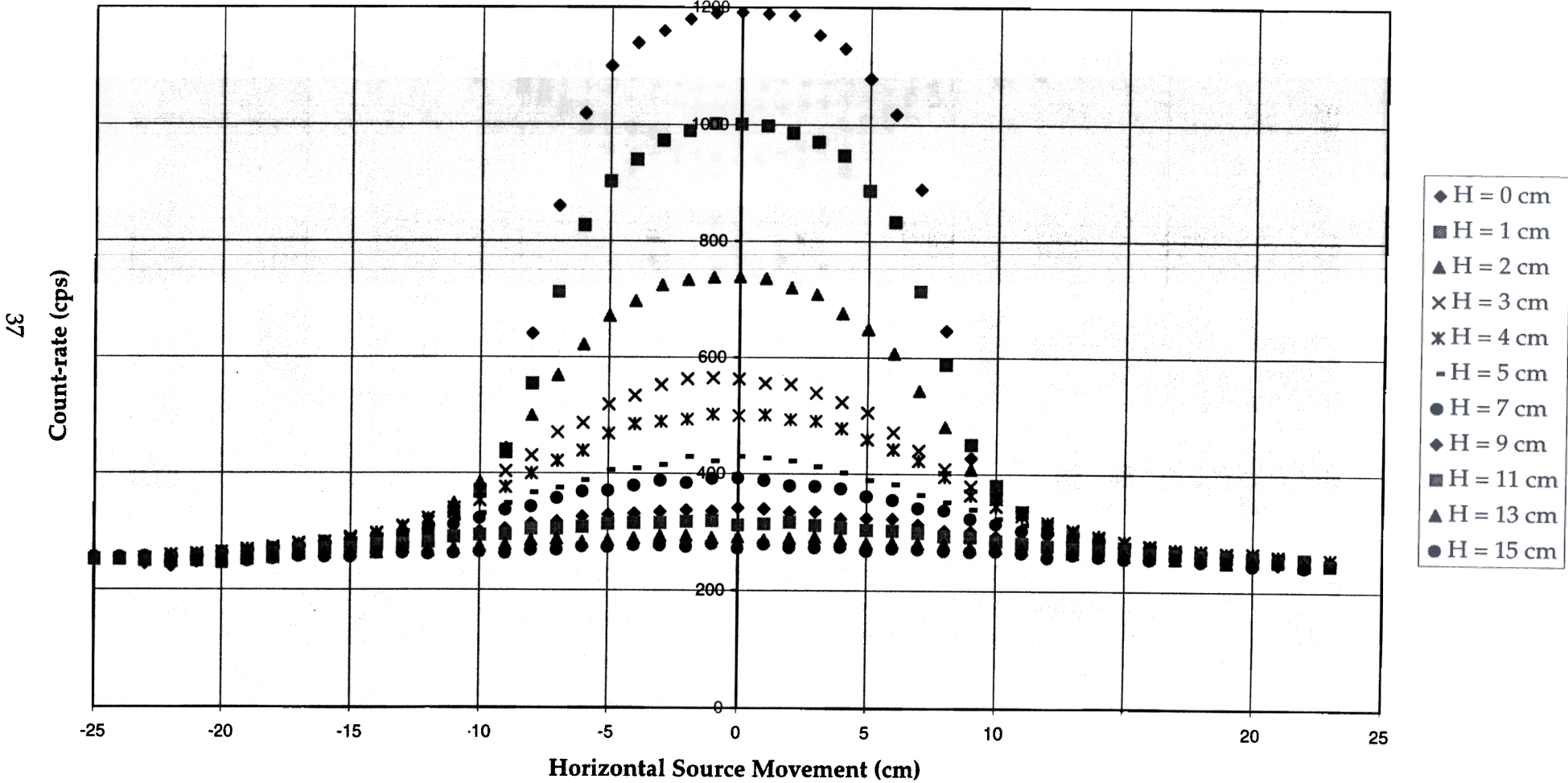


Figure 19

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation, Cs-137 and GP13 (short orientation)

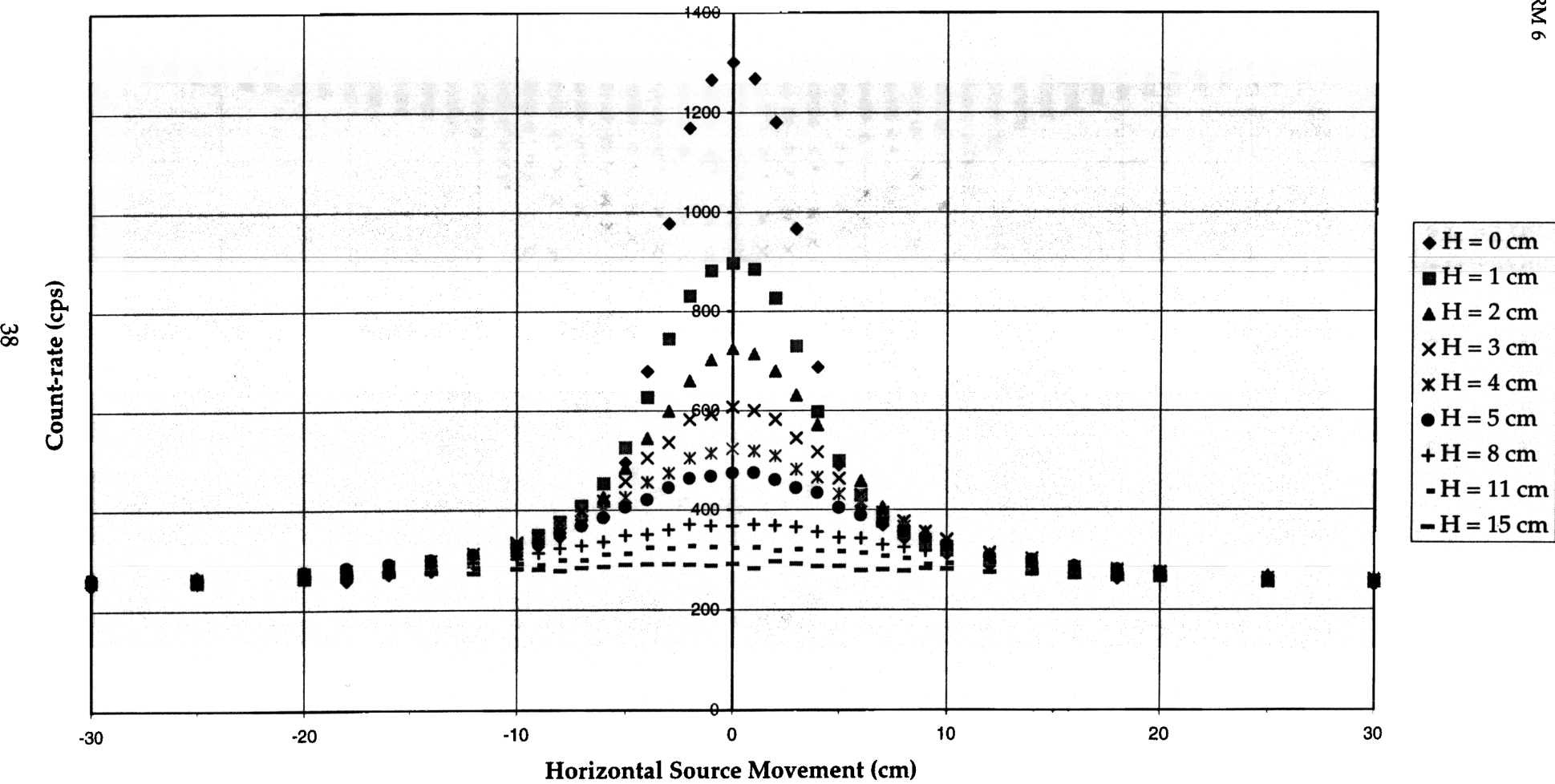


Figure 20

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation,
Co-57 and G2

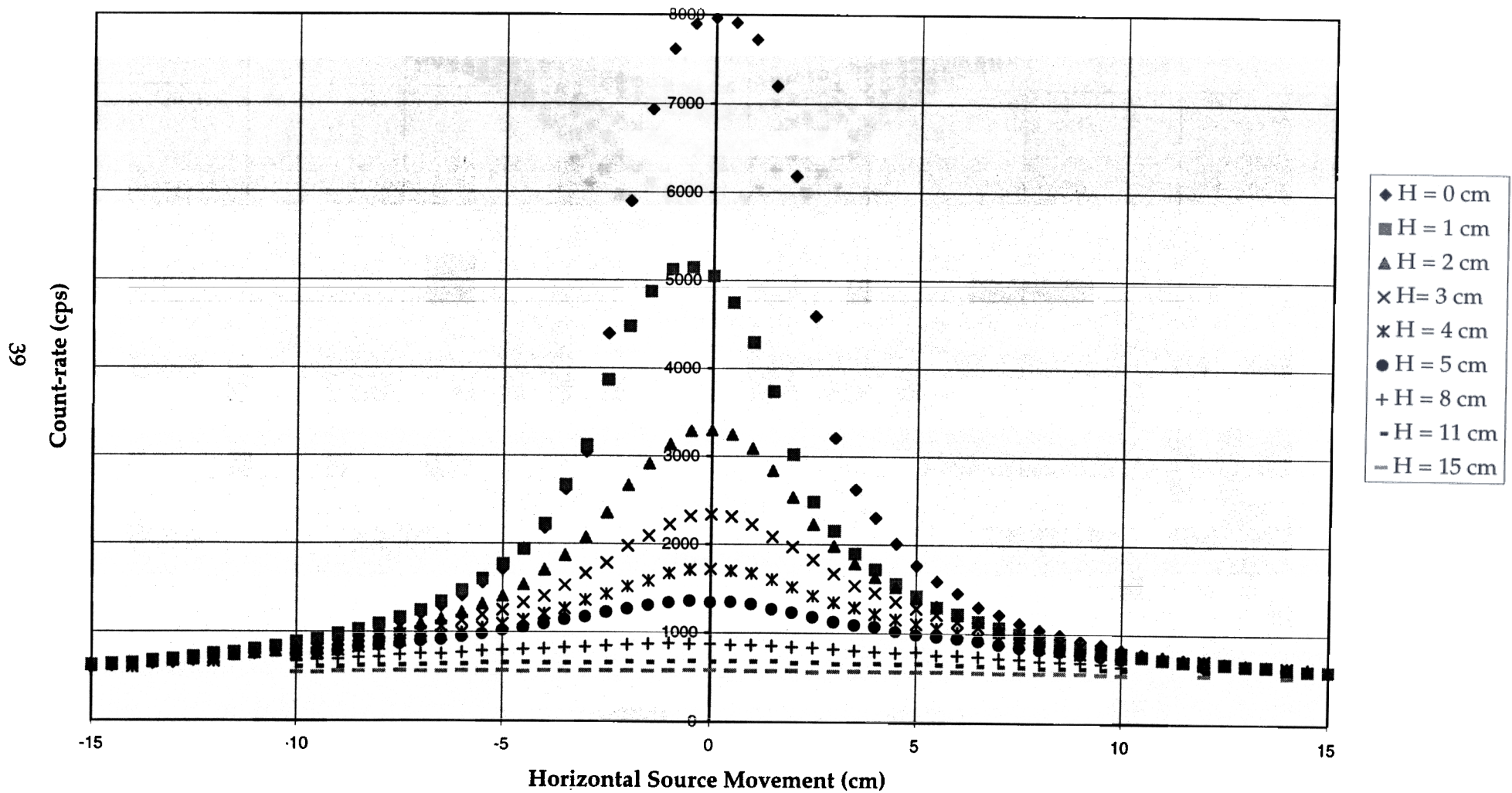


Figure 21

Variation of Detector Response with Horizontal Source Movement and Source - Detector Separation,
Cs-137 and G2

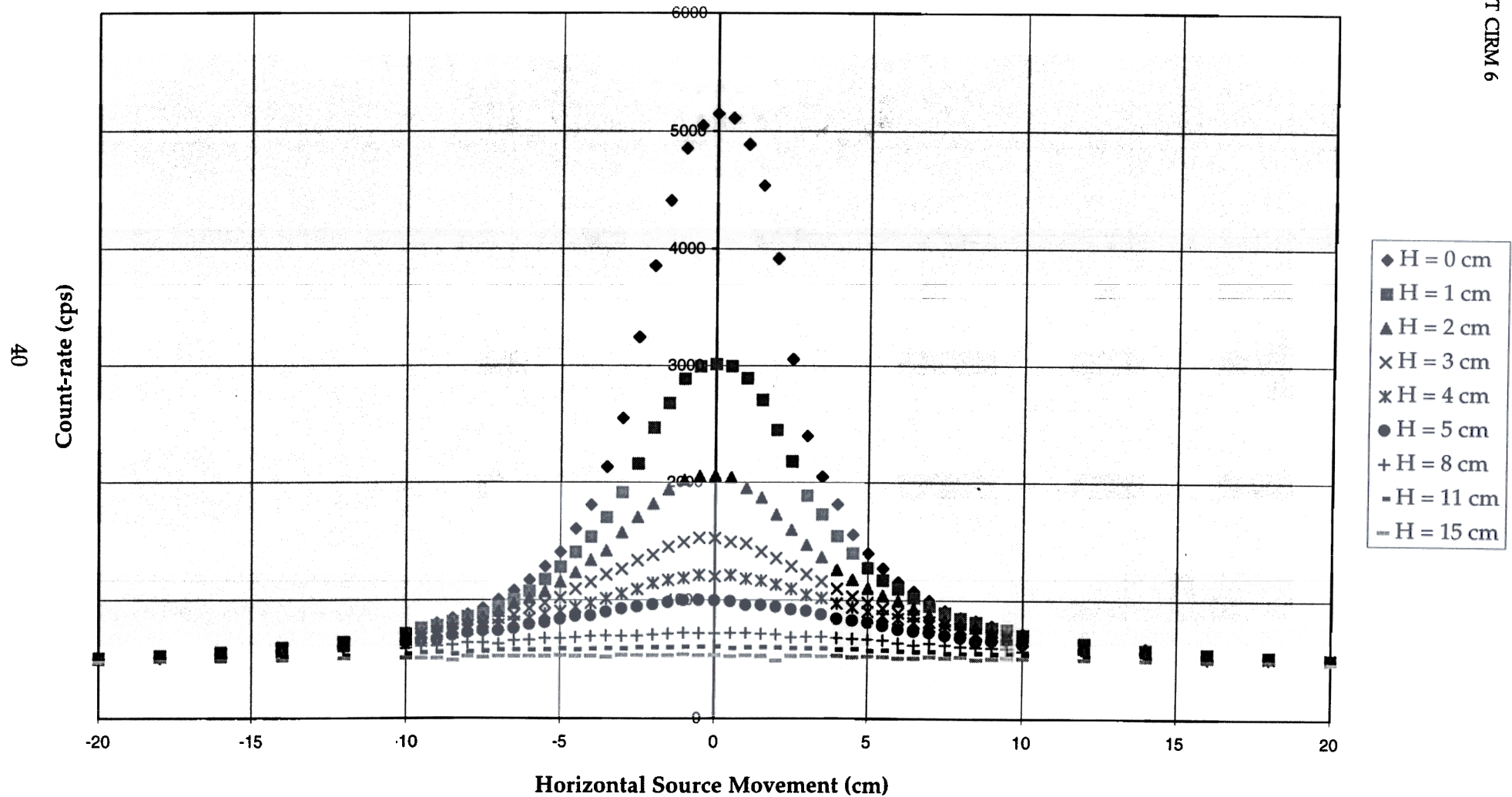
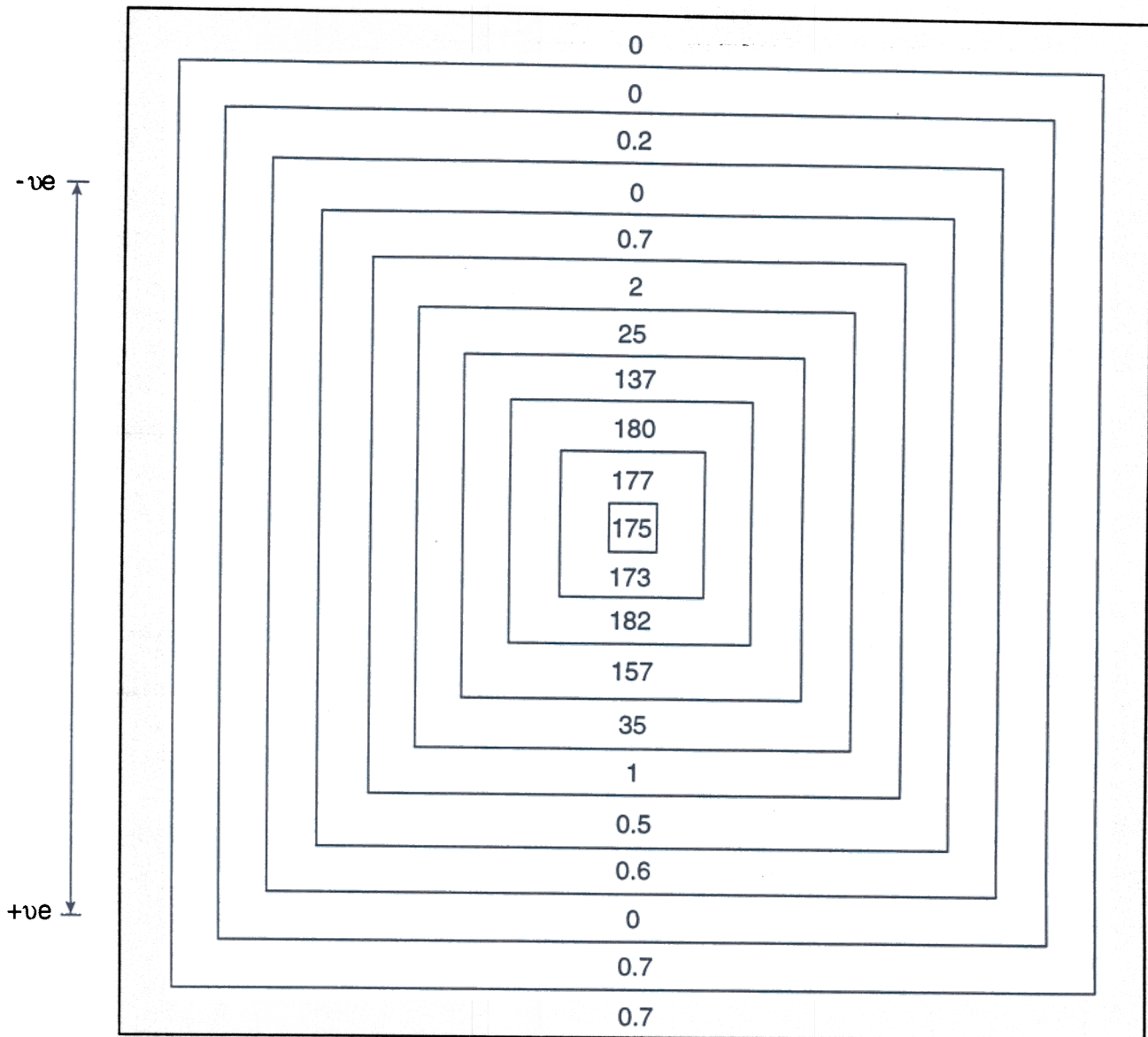


Figure 22

Annular Plot of Detector Response for the DP2 Probe with ^{234}U 

The diagram shows the detector responses (cps), observed by the DP2 probe when a ^{234}U point source was moved at 1 cm intervals in each direction from the origin (where the source and probe were concentric).

Figure 23

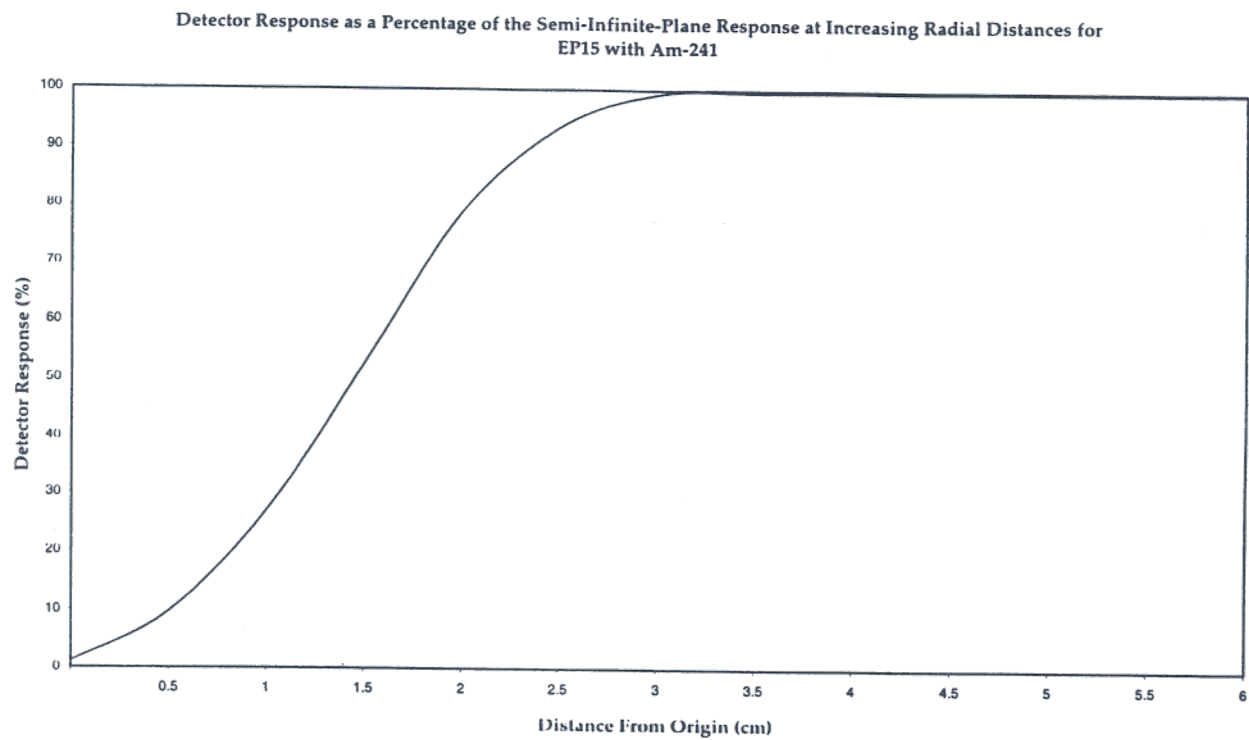


Figure 24

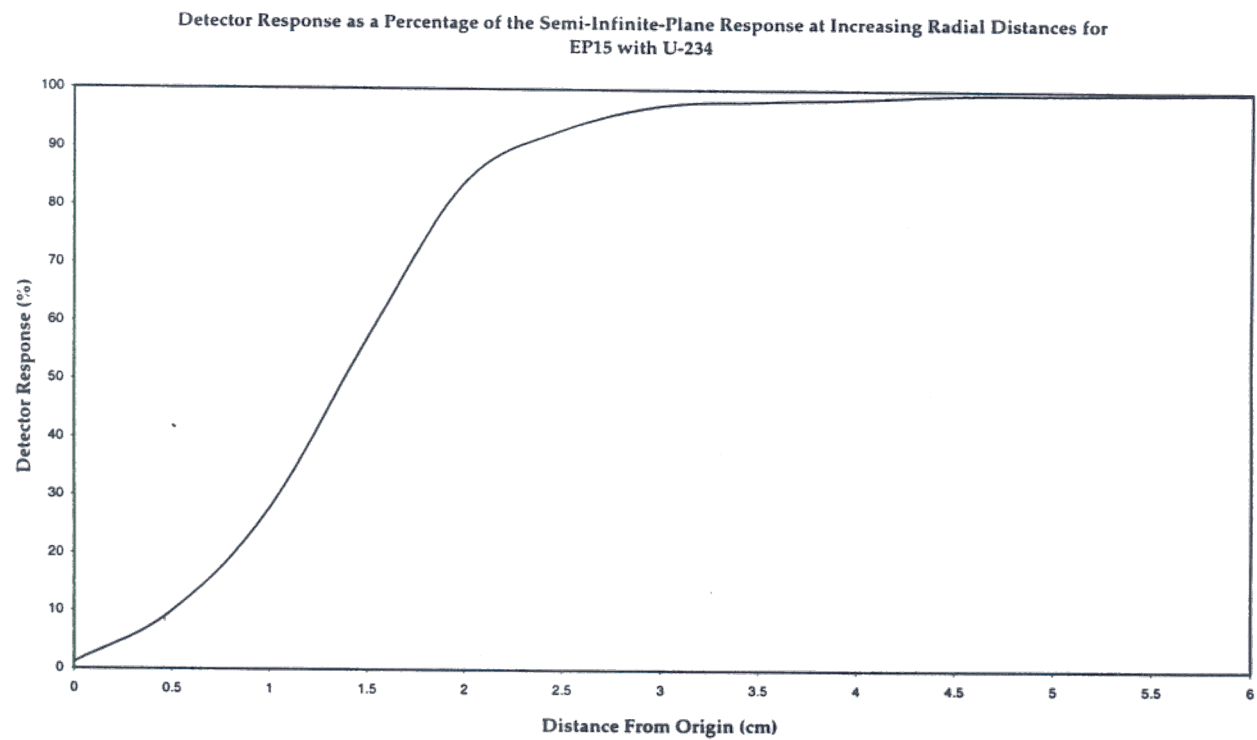


Figure 25

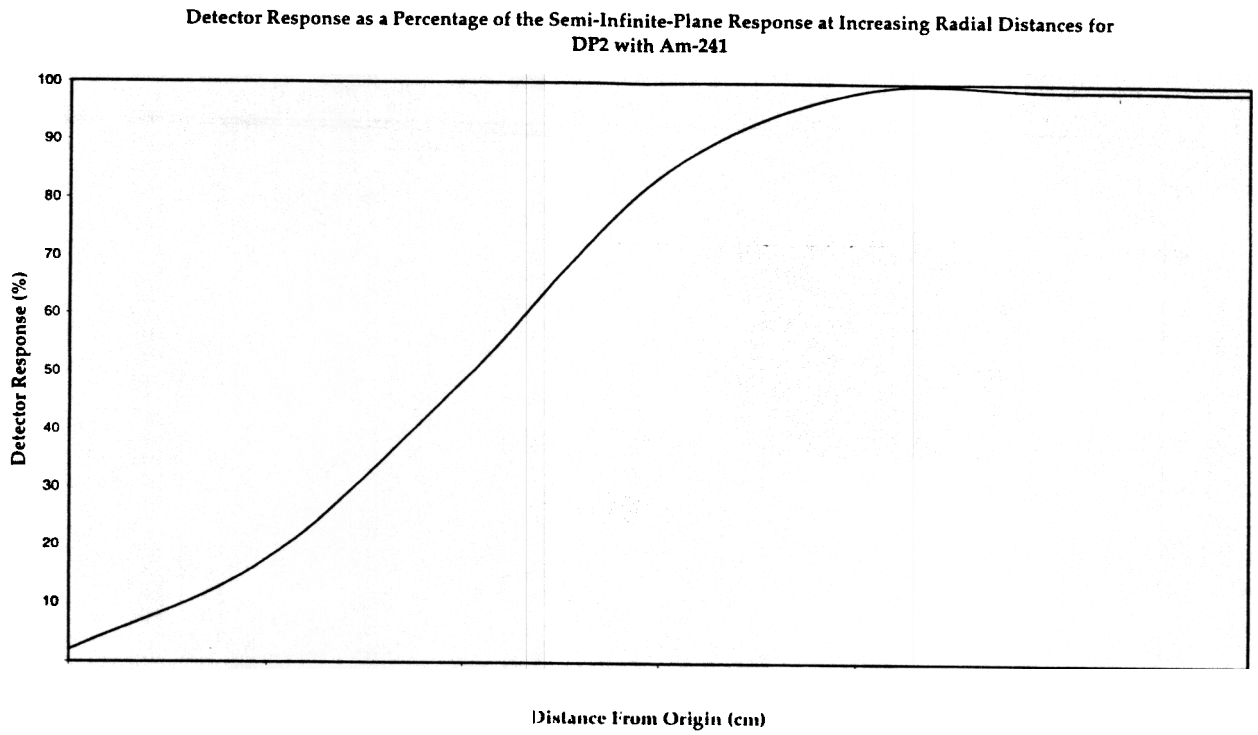


Figure 26

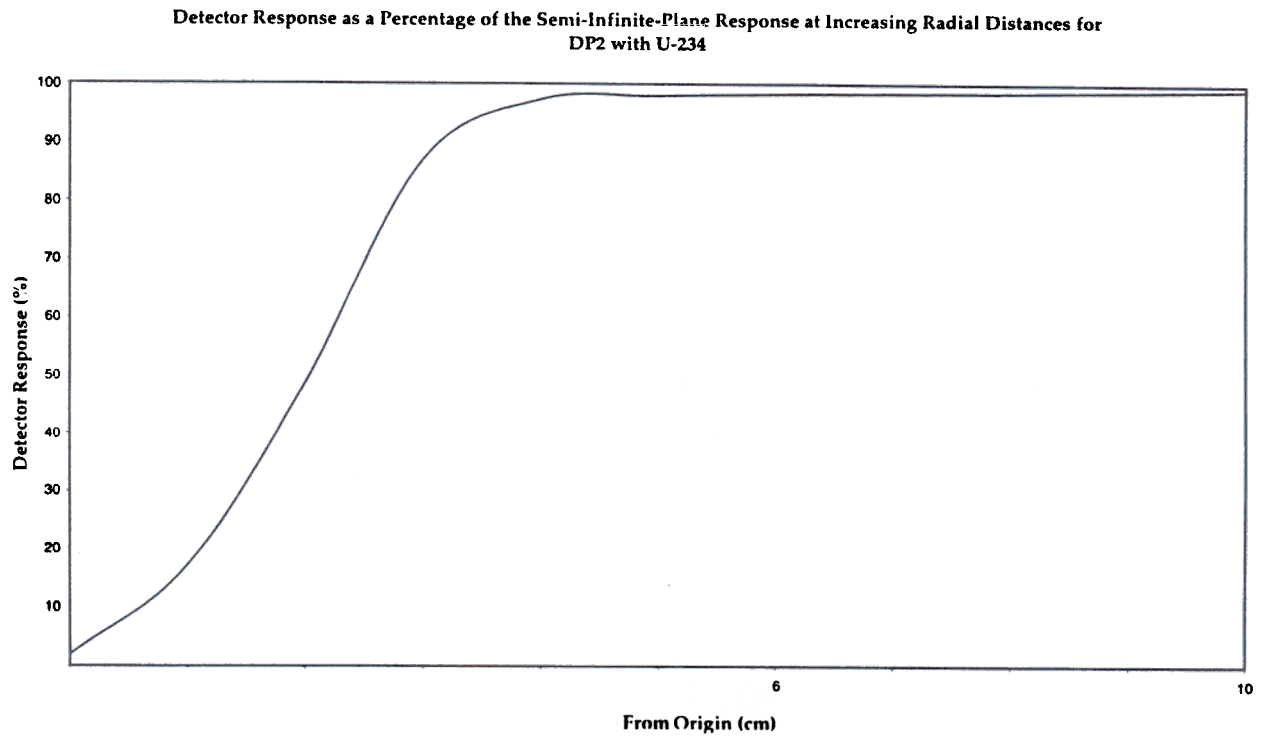


Figure 27

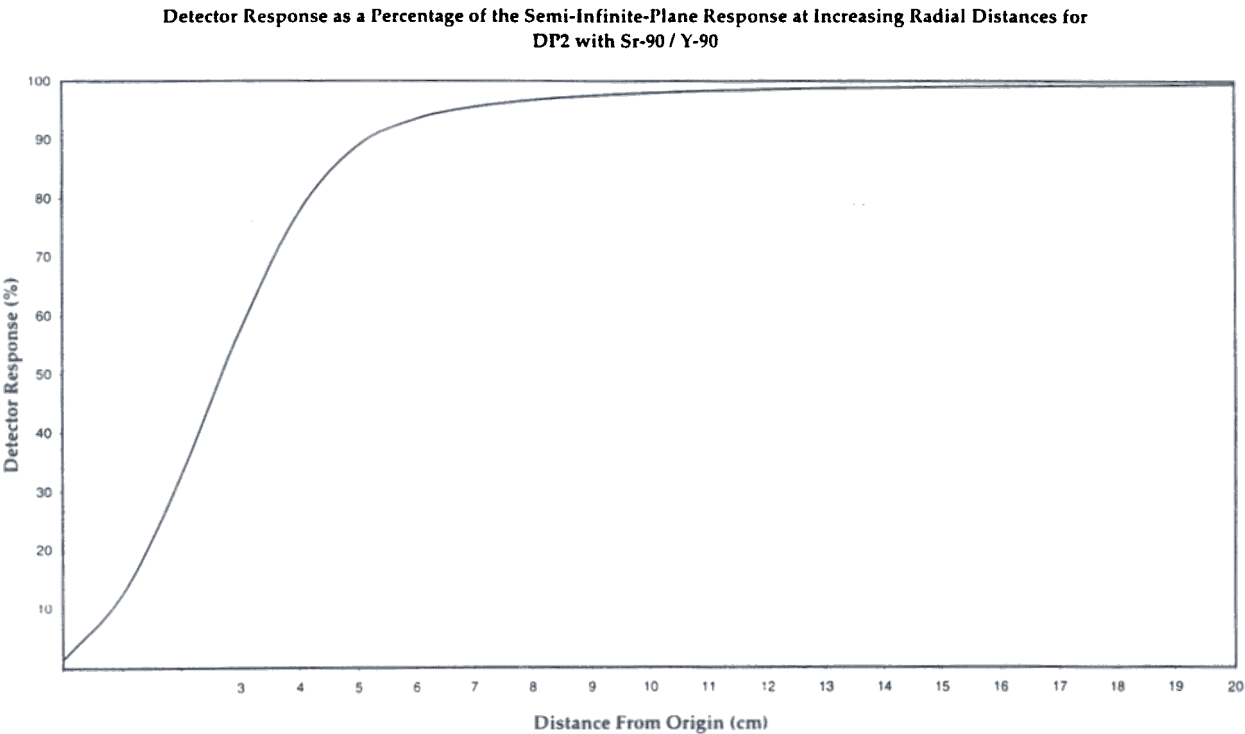


Figure 28

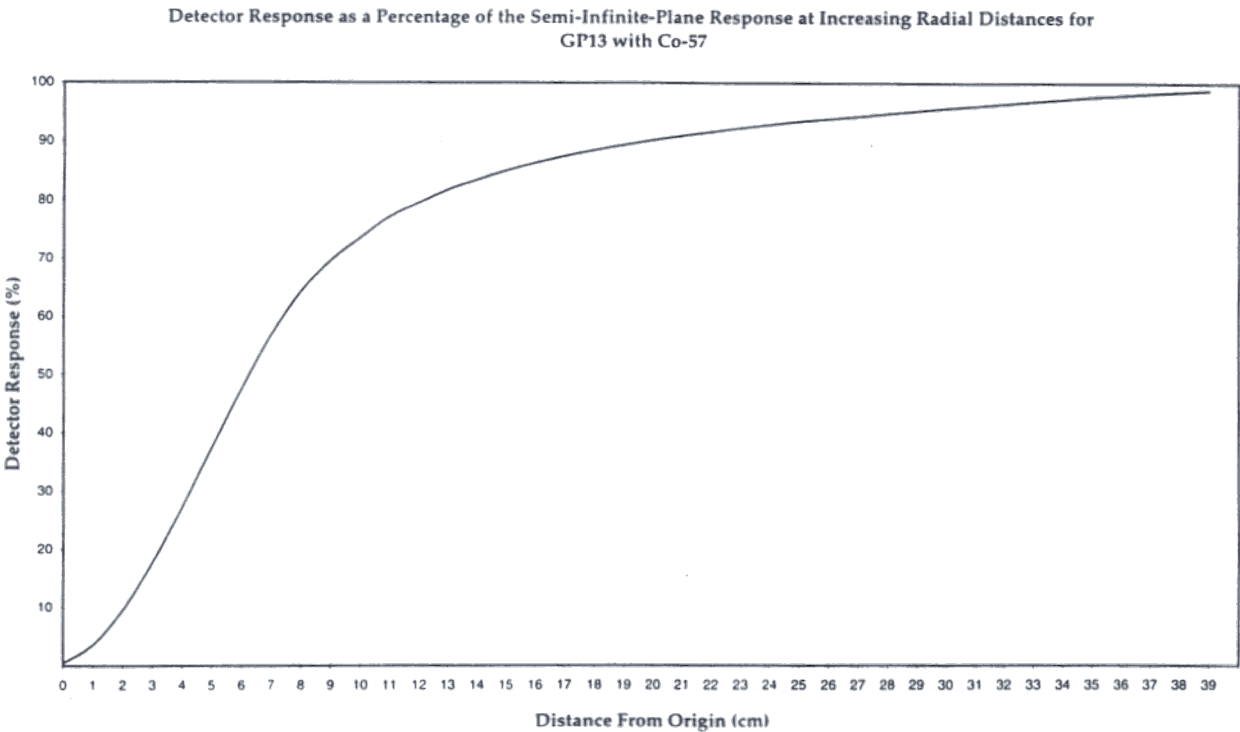


Figure 29

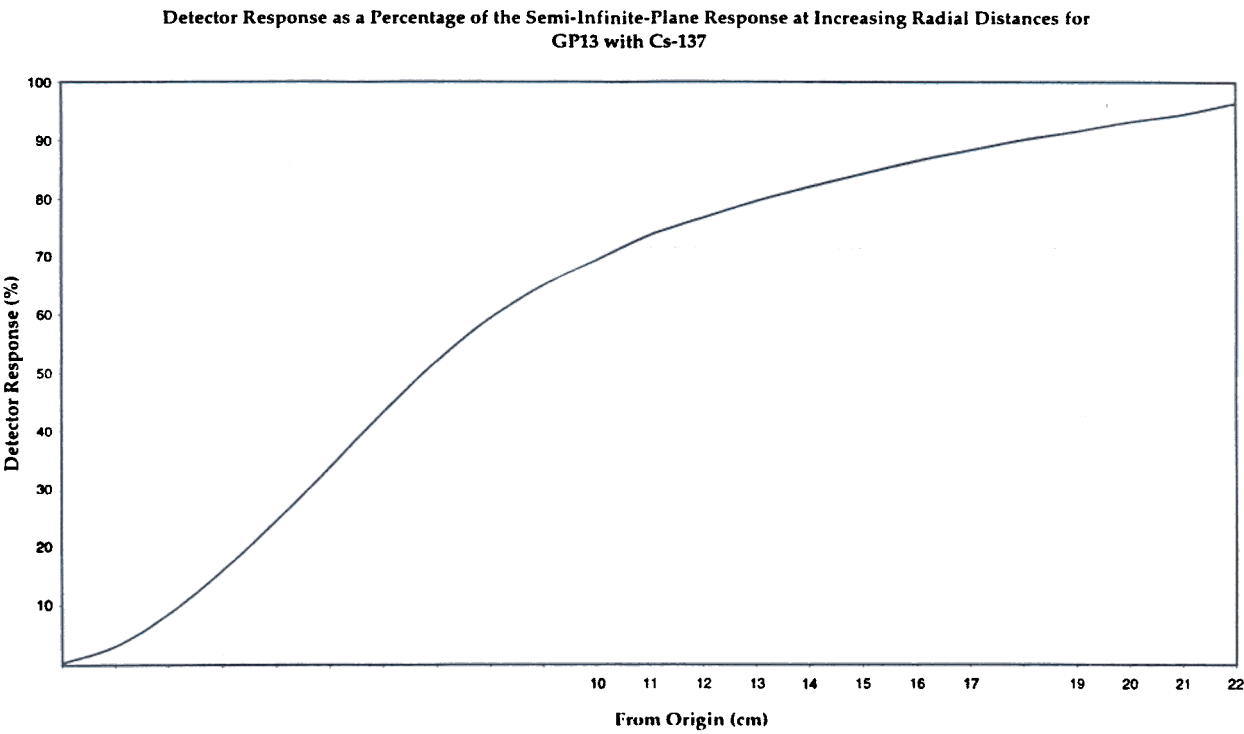


Figure 30

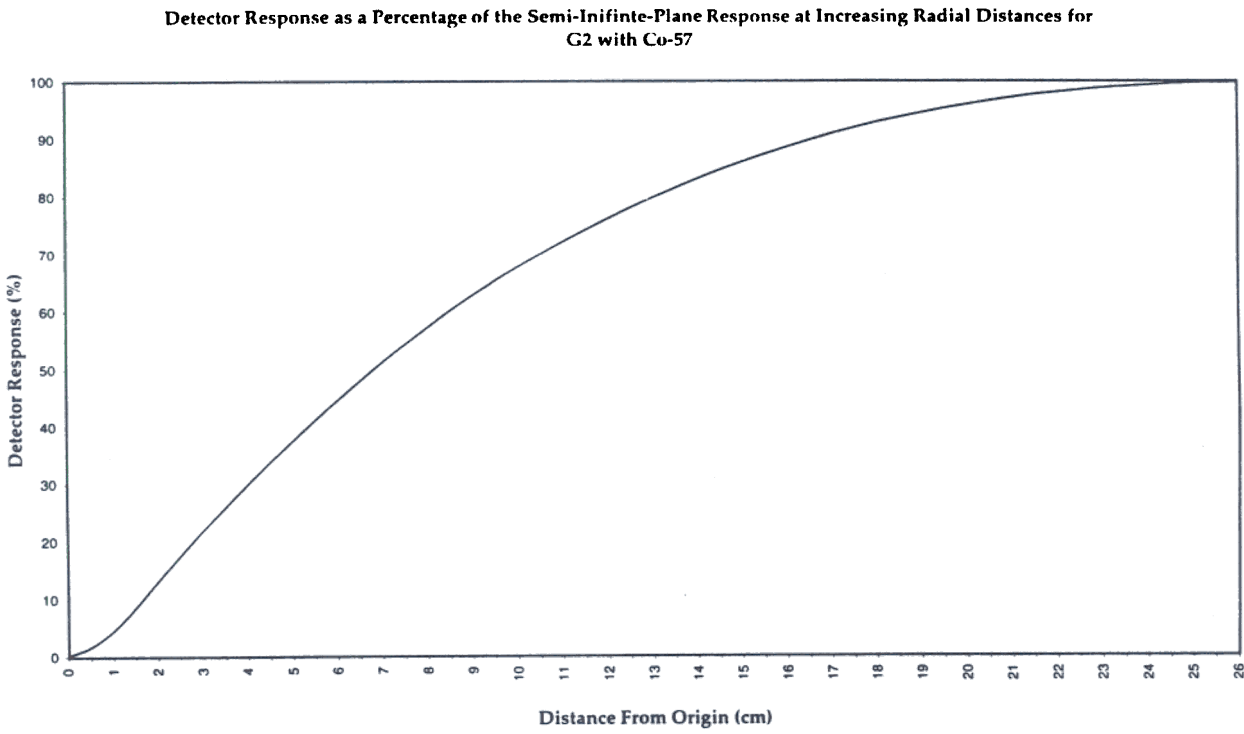


Figure 31

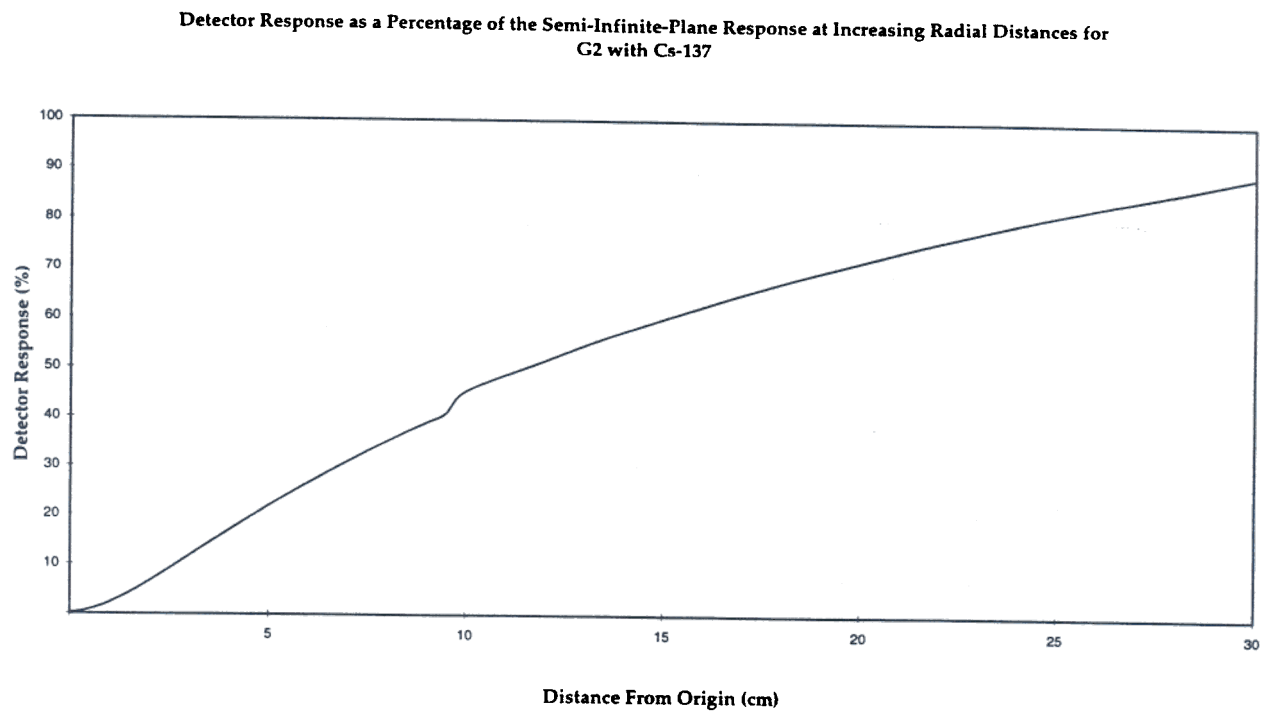


Figure 32 Uniformity of ^{241}Am : Percentage Deviations from Mean Counts

1 + 4.0 %	2 + 3.1 %	3 + 6.4 %
4 - 4.7 %	5 - 2.2 %	6 + 1.4 %
7 - 5.1 %	8 - 4.7 %	9 + 1.7 %

Overall Uniformity (ISO 8769) equivalent to 4.3 %

Figure 33 Uniformity of ^{234}U : Percentage Deviations from Mean Counts

1 - 20.3 %	2 - 29.7 %	3 - 16.5 %
4 - 12.2 %	5 - 3.6 %	6 - 0.8 %
7 + 14.2 %	8 + 35.9 %	9 + 33.0 %

Overall Uniformity (ISO 8769) equivalent to 23 %

Figure 34 Uniformity of $^{90}\text{Sr}/^{90}\text{Y}$: Percentage Deviations from Mean Counts

1 - 18.5 %	2 - 10.8 %	3 - 9.2 %
4 - 6.0 %	5 + 0.6 %	6 - 0.8 %
7 + 15.6 %	8 + 17.9 %	9 + 11.1 %

Overall Uniformity (ISO 8769) equivalent to 12.6 %

Figure 35 Uniformity of ^{14}C : Percentage Deviations from Mean Counts

1 - 24.0 %	2 - 1.5 %	3 - 1.1 %
4 + 13.2 %	5 - 0.9 %	6 + 9.0 %
7 + 6.1 %	8 + 2.1 %	9 - 2.9 %

Overall Uniformity (ISO 8769) equivalent to 10.5 %

Figure **Uniformity** **^{137}Cs** **Percentage Deviation from Mean Counts**

1 - 2.2 %	2 + 6.0 %	3 + 6.0 %	4 + 1.9 %
5 - 8.1 %	6 + 0.6 %	7 + 5.8 %	8 + 2.2 %
9 + 4.5 %	10 + 6.0 %	11 + 6.7 %	12 + 1.2 %
13 - 6.4 %	14 - 11.6 %	15 - 5.2 %	16 - 7.3 %

Overall Uniformity (ISO 8769) equivalent to %

Figure **Uniformity** **^{137}Cs** **Percentage Deviation from Mean Counts**

1 - 0.8 %	2 + 1.1 %	3 + 6.0 %	4 + 10.4 %
5 - 8.1 %	6 + 3.8 %	7 + 6.3 %	8 + 1.1 %
9 - 7.8 %	10 + 4.7 %	11 + 5.1 %	12 + 2.0 %
13 + 11.7 %	14 - 11.2 %	15 - 14.2 %	16 - 10.1 %

Overall Uniformity (ISO 8769) equivalent to %

Figure 38

**Deviation from the Mean Value of the Detector Responses Obtained
from 25 Pieces of the Very Large Area Source**

1 - 3.13 %	2 + 1.84 %	3 + 5.15 %	4 + 13.43 %	5 - 6.03 %
6 - 3.96 %	7 + 0.18 %	8 + 3.08 %	9 + 7.22 %	10 - 7.68 %
11 - 4.79 %	12 + 0.60 %	13 - 0.23 %	14 + 7.22 %	15 - 9.75 %
16 - 6.03 %	17 - 0.65 %	18 + 0.60 %	19 + 8.88 %	20 - 4.79 %
21 - 2.72 %	22 - 2.30 %	23 + 4.32 %	24 + 5.98 %	25 - 6.44 %

Overall Uniformity (ISO 8769) equivalent to 5.8 %

Mean observed countrate : 140 s^{-1} (background corrected)

Background countrate : 102 s^{-1}

Figure 39

**Observed Count-rates (s^{-1}) Using the Contiguous Portions Technique
with the Source in 25 Different Positions Relative to the Detector**

1 4 ± 3	2 5 ± 3	3 5 ± 3	4 3 ± 3	5 3 ± 3
6 3 ± 3	7 11 ± 3	8 18 ± 3	9 11 ± 3	10 5 ± 3
11 6 ± 3	12 35 ± 3	13 102 ± 3	14 43 ± 3	15 6 ± 3
16 4 ± 3	17 9 ± 3	18 17 ± 3	19 10 ± 3	20 4 ± 3
21 2 ± 3	22 4 ± 3	23 4 ± 3	24 3 ± 3	25 2 ± 3

Background countrate : $148 s^{-1}$ (data corrected)

These data were collected using the GP13 at a height of 3 mm (above the filter) over a 100×100 mm piece of the very large area ^{137}Cs source.

The apparently large uncertainties quoted are due to poor statistics when the net countrates are low.

Figure 40

Source Positioning Errors

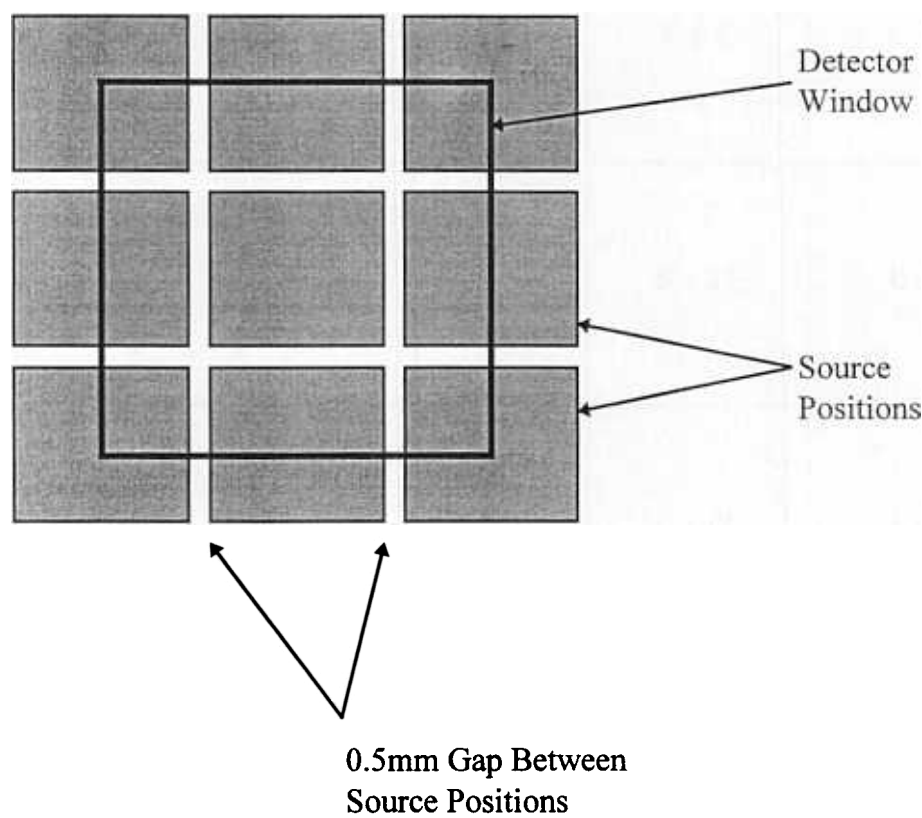


Table 1**Monitors Employed**

Probe	Manufacturer	Abbreviated Name	Probe Type	Detector Area
BP7/4A	NE Technology	BP7	Scintillator	70 x 70 mm
DP2R/4A	NE Technology	DP2	Dual Scintillator	70 x 70 mm
900EP15	Mini Instruments	EP15	Geiger-Müller	58 mm diameter
G2	NE Technology	G2	Thick NaI	58 mm diameter
GP13A	NE Technology	GP13	Scintillator	67 x 150 mm

Table 2

Radioactive Sources

Radionuclide	Active Area (mm)	Substrate Area (mm)	ISO Filter
^{14}C	point	20 x 20	none
	100 x 100	100 x 100	
^{57}Co	point	20 x 20	200 mg.cm ⁻² (0.25 mm) stainless steel
	100 x 100	100 x 100	
^{90}Sr	point	20 x 20	none
	100 x 100	100 x 100	
^{137}Cs	point	20 x 20	800 mg.cm ⁻² (1.02 mm) stainless steel
	100 x 100	100 x 100	
	500 x 500	500 x 500	
^{234}U	point	20 x 20	none
	100 x 100	100 x 100	
^{241}Am	point	20 x 20	ISO filter not required for this application
	100 x 100	100 x 100	

Table 3

Detector Profiles Examined

Monitor	Point Source	Probe Orientation
EP15	^{241}Am	Normal
EP15	^{234}U	Normal
DP2	^{241}Am	Normal
DP2	^{234}U	Normal
DP2	$^{90}\text{Sr}/\text{Y}$	Normal
DP2	$^{90}\text{Sr}/\text{Y}$	Diagonal
GP13	^{57}Co	Long
GP13	^{57}Co	Short
GP13	^{57}Co	Diagonal
GP13	^{137}Cs	Long
GP13	^{137}Cs	Short
G2	^{57}Co	Normal
G2	^{137}Cs	Normal

Table 4 **Detector Profile for EP15 with ^{241}Am : Mean Detector Response for Height (H)**

Distance from Origin (cm)	Mean Detector Reponse (s^{-1}) at Height H (cm)					
	0	1	2	3	4	5
-6	-	0.5	0	0.3	0.8	0.3
-5.5	-	1	-	-	-	-
-5.0	0.6	0	0.9	2	2	0
-4.5	0.3	0.8	-	-	-	-
-4.0	0	0.8	2	2	0	0.9
-3.5	0.5	5	-	-	-	-
-3.0	21	128	5	3	0.5	2
-2.5	586	335	5	0.7	0.7	1
-2.0	583	541	7	3	0.7	0.3
-1.5	582	590	10	3	2	0.9
-1.0	581	589	9	3	2	1
-0.5	576	587	5	3	1	0.8
0	579	590	9	4	2	0.5
0.5	579	588	5	2	2	1
1.0	580	589	7	4	1	2
1.5	583	574	7	1	1	0.3
2.0	575	349	5	0.8	2	0.3
2.5	76	65	3	1	1	0
3.0	0.6	7	2	1	0	0.2
3.5	0	1	-	-	-	-
4.0	0	0.1	1	0.3	0.6	2
4.5	0	0	-	-	-	-
5.0	0	0	0.4	0.8	0	0
5.5	-	-	-	-	-	-
6.0	-	-	0.6	0	0.5	0.3

This data is the difference observed between measurements performed with (γ) and without ($\alpha + \gamma$) a sheet of paper placed over the source and indicates the detector response due to alpha emissions only.

Mean background : 1.1 s^{-1} (data corrected)

Table 5 **Detector Profile for EP15 with ^{234}U : Mean Detector Response for Height (H)**

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	7	9	11
7	-	-	0.3	0.2	0.1	0	-	-	-
6.5	-	-	0	0.5	0.8	0.8	-	-	-
6	0	0	0.4	0.1	0.3	0	0.4	-	-
5.5	0.2	0.2	1	1	0	0	0.4	-	-
5	0.2	0	1	0.8	0	0.6	1	-	-
4.5	0	0.4	0.4	0.1	1	0.6	1	-	-
4	0.9	0.7	1	1	1	0	0.2	-	-
3.5	0.7	0.6	2	0.7	0.3	0.1	0.3	-	-
3	4	5	0.7	1	0.6	0.7	0.5	0.3	-
2.5	80	12	3	2	2	0	0	0.6	-
2	397	42	2	1	2	2	0.8	0.8	-
1.5	567	62	4	3	3	0.1	0.6	0	-
1	558	61	7	2	0	0.6	0.1	0.4	0
0.5	545	60	8	3	2	0.8	0.3	0.6	0.3
0	550	58	9	4	1	2	1	0	0
-0.5	545	66	4	2	2	1	0.8	0	0
-1	562	67	7	7	0	3	0.6	0	0
-1.5	568	78	8	0.4	0.5	2	0.3	0.9	-
-2	408	53	7	2	1	2	0	0.5	-
-2.5	84	13	3	2	3	0.3	0.3	0.1	-
-3	1	5	2	2	2	0.7	1	0	-
-3.5	0.2	1	2	1	0.1	0.4	0	-	-
-4	0.2	0	1	0	0.2	0.8	0.5	-	-
-4.5	0.1	0.8	2	0.4	0.5	1	0.2	-	-
-5	0.5	0.1	0	1	0.2	0.1	0	-	-
-5.5	0.6	0	0.9	0.5	0.6	0	0.2	-	-
-6	0.2	0.2	0.4	0.7	0.2	0	0.2	-	-
-6.5	-	-	0	0.5	0	0.2	-	-	-
-7	-	-	0.8	0.4	0	0	-	-	-
-7.5	-	-	-	-	-	0	-	-	-
-8	-	-	-	-	-	0.6	-	-	-

Table 6 **Detector Profile for DP2 with ^{241}Am : Mean Detector Responses for Height (H)**

Distance from Origin (cm)	Mean Detector Reponse (s^{-1}) at Height H (cm)			
	0	1	2	3
-7	-	-	-	0
-6	0.9	0	0.6	0.3
-5	0	11	0.3	0
-4	43	401	75	0.1
-3	2073	1030	272	0
-2	2196	1304	329	0.8
-1	2161	1306	323	1
0	2154	1293	317	0.1
1	2106	1290	322	0
2	2150	1259	329	0
3	1834	924	255	0.7
4	0.3	212	64	0
5	0.2	1	0	0.1
6	0	0.6	0.2	0.5
7	-	-	-	0

This data is the difference between measurements performed with (γ) and without ($\alpha + \gamma$) a sheet of paper placed over the source and indicates the detector response due to alpha emissions only.

Mean background : 5 s^{-1} (data corrected)

Table 7 **Detector Profile for DP2 with ^{234}U : Mean Detector Response for Height (H)**

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)						
	0	1	2	3	4	5	6
-13	-	0	-	-	-	-	-
-12	-	0	-	-	-	0	-
-11	0	0	-	-	0.1	0.3	-
-10	0.5	0	0	0.4	0.3	0.8	0
-9	0.7	0	0.2	0	0	0	1
-8	0.6	0.2	0.1	0.7	0.3	0	0
-7	0.3	0	0	1	0	0.4	0
-6	0	0.7	0	0.3	0.5	0	0.2
-5	0.4	2	2	0.9	0.3	0	0.9
-4	51	25	4	2	1	0.3	0
-3	698	137	9	3	1	0.6	0.3
-2	846	180	16	4	2	2	0
-1	824	177	15	4	2	1	0.1
0	809	175	15	5	2	0.8	2
1	795	173	15	5	1	0.2	0.7
2	807	182	16	3	0.9	1	0.3
3	753	157	12	2	1	0.5	0
4	73	35	5	2	1	0.3	0.8
5	0	1	1	0	1	0.2	0
6	0.1	0.5	0.3	0	0.6	0	0.7
7	0.1	0.6	0.4	0.1	0	0.8	0
8	0.1	0	0.3	0	0.1	0	0.1
9	0.7	0.7	0.6	0.2	0	0	-
10	0	0.7	0	0	0	0.2	-
11	0.7	-	0	-	0	-	-
12	-	-	0.1	-	-	-	-

This data is the difference between measurements performed with (γ) and without ($\alpha + \gamma$) a sheet of paper placed over the source and indicates the detector response to alpha emissions only.

Mean background : 5.1 s^{-1} (data corrected)

Table 8 **Detector Profile for DP2 with $^{90}\text{Sr}/^{90}\text{Y}$: Mean Detector Response for Height (H)**

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)										
	0	1	2	3	4	5	7	9	11	13	15
-37	-	-	-	-	-	-	-	-	-	-	16
-36	-	-	-	-	-	-	-	-	15	16	17
-35	-	-	-	-	-	-	-	-	15	16	17
-34	-	-	-	-	-	-	-	-	16	17	18
-33	-	-	-	-	-	-	-	14	17	17	18
-32	-	-	-	-	-	-	13	14	17	17	19
-31	-	-	-	-	-	-	13	15	18	18	19
-30	-	-	-	-	-	-	14	17	18	19	23
-29	-	-	-	-	-	-	15	18	20	21	22
-28	-	-	-	-	-	-	15	17	22	22	25
-27	-	-	-	-	-	-	16	19	21	22	27
-26	-	-	-	-	-	13	17	21	24	23	28
-25	-	-	-	-	-	13	18	23	26	26	28
-24	-	-	-	-	-	15	19	25	28	28	32
-23	-	-	-	-	-	16	21	26	31	32	34
-22	-	-	-	12	12	17	22	29	34	35	37
-21	-	-	-	12	15	19	25	32	36	39	40
-20	-	-	-	14	15	21	27	35	40	43	45
-19	-	-	-	15	18	24	32	38	47	46	48
-18	-	-	-	16	20	26	35	46	52	55	51
-17	-	-	13	17	27	32	41	52	60	60	58
-16	-	-	14	20	27	37	48	60	65	65	64
-15	-	11	15	25	31	45	58	69	76	75	70
-14	-	12	20	31	42	55	70	81	87	84	76
-13	-	15	26	39	51	69	84	97	98	94	87
-12	-	16	31	49	64	86	105	113	109	106	95
-11	-	20	42	67	84	113	124	134	131	116	104
-10	9	27	60	90	116	148	155	155	154	133	113
-9	9	43	86	135	159	197	198	188	171	143	124
-8	10	67	136	200	231	265	250	225	194	162	132
-7	12	114	228	313	337	351	304	260	220	177	143
-6	16	255	397	503	500	472	370	306	241	194	156
-5	32	612	717	766	719	626	444	347	267	210	167
-4	300	1573	1260	1180	974	787	520	384	291	223	173
-3	3855	2686	1882	1587	1241	942	600	424	310	232	182
-2	4647	3383	2408	1923	1477	1074	659	455	327	243	187
-1	4644	3692	2674	2129	1628	1157	699	472	339	247	190
0	4661	3749	2811	2191	1694	1196	714	487	340	250	194
1	4656	3651	2728	2112	1635	1156	699	475	335	244	191

Table 8 continued

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)										
	0	1	2	3	4	5	7	9	11	13	15
2	4617	3291	2480	1909	1512	1063	666	454	332	240	190
3	4145	2494	2030	1586	1287	934	604	423	306	235	184
4	518	1273	1384	1151	1004	797	547	388	294	220	177
5	38	474	807	759	737	625	468	344	264	208	165
6	18	222	463	486	513	475	389	309	238	193	158
7	13	109	254	310	355	358	320	266	212	175	150
8	10	65	150	191	245	266	263	221	187	159	138
9	10	38	95	130	174	198	214	193	166	143	127
10	9	27	64	92	121	154	173	160	145	130	117
11	-	20	46	64	92	113	136	137	127	114	105
12	-	17	33	49	68	89	109	113	107	101	94
13	-	13	26	39	53	68	94	92	96	90	88
14	-	12	21	31	43	58	76	82	87	82	81
15	-	11	17	23	34	45	62	70	72	75	74
16	-	-	16	22	28	39	54	61	62	67	68
17	-	-	14	18	24	30	47	52	54	61	59
18	-	-	-	16	21	28	40	44	50	51	52
19	-	-	-	15	18	24	33	39	42	47	49
20	-	-	-	13	17	21	29	35	39	43	46
21	-	-	-	12	16	19	27	31	34	39	42
22	-	-	-	11	14	17	25	28	32	35	36
23	-	-	-	-	12	15	22	25	29	31	35
24	-	-	-	-	-	17	20	22	26	29	32
25	-	-	-	-	-	13	20	21	23	28	29
26	-	-	-	-	-	12	18	20	21	26	27
27	-	-	-	-	-	-	16	18	20	25	26
28	-	-	-	-	-	-	16	17	19	23	26
29	-	-	-	-	-	-	16	16	17	21	23
30	-	-	-	-	-	-	14	16	18	20	22
31	-	-	-	-	-	-	14	15	15	19	20
32	-	-	-	-	-	-	13	16	15	19	20
33	-	-	-	-	-	-	-	14	15	18	18
34	-	-	-	-	-	-	-	-	14	16	18
35	-	-	-	-	-	-	-	-	13	17	16
36	-	-	-	-	-	-	-	-	13	15	16
37											16

See Table 9 for profile in diagonal direction.
Mean background : $9 s^{-1}$ (data not corrected)

Table 9 **Detector Profile for DP2 in Diagonal Direction with $^{90}\text{Sr}/^{90}\text{Y}$:
Mean Detector Response for a Height of 1 cm**

Distance from Origin (cm)	Mean Detector Response (s^{-1})
-20	9
-19	9
-18	10
-17	9
-16	10
-15	10
-14	12
-13	12
-12	15
-11	18
-10	22
-9	30
-8	50
-7	105
-6	294
-5	947
-4	1979
-3	2921
-2	3459
-1	3686
0	3762

Distance from Origin (cm)	Mean Detector Response (s^{-1})
1	3684
2	3475
3	2929
4	2017
5	1034
6	296
7	111
8	52
9	32
10	22
11	19
12	15
13	13
14	10
15	11
16	11
17	10
18	10
19	10
20	10

Mean background : 8 s^{-1} (data not corrected)

Table 10

Detector Profile for GP13 with ^{57}Co : Mean Detector Response for Height (H)

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)										
	0	1	2	3	4	5	7	9	11	13	15
-40	-	-	-	-	-	-	-	-	-	257	246
-39	-	-	-	-	-	-	-	-	263	263	253
-38	-	-	-	-	-	-	261	-	268	265	258
-37	-	-	-	-	-	259	263	-	265	271	256
-36	-	-	-	-	-	258	266	267	269	269	260
-35	-	-	-	-	256	267	269	270	273	272	263
-34	-	-	-	-	263	264	271	274	275	272	262
-33	-	-	-	-	262	269	274	276	279	279	274
-32	-	-	-	266	269	265	276	277	276	276	276
-31	-	-	-	267	272	273	281	282	283	285	281
-30	-	-	256	274	267	273	278	291	291	291	279
-29	-	-	268	275	271	277	288	295	290	286	289
-28	-	-	268	273	281	284	289	294	294	292	290
-27	-	-	273	285	283	284	293	302	297	302	300
-26	-	-	276	285	290	297	300	308	308	306	299
-25	-	-	276	293	299	300	315	319	312	311	309
-24	-	269	283	300	297	313	317	321	320	320	305
-23	257	280	291	306	306	318	325	329	322	329	320
-22	267	281	299	317	320	332	339	340	340	340	324
-21	267	290	306	330	327	340	349	346	350	340	331
-20	276	296	321	341	346	353	365	363	359	353	339
-19	279	302	332	362	367	375	378	378	373	360	350
-18	288	322	352	380	385	396	391	399	382	373	357
-17	297	338	379	404	412	421	419	415	397	388	367
-16	305	353	404	438	441	456	444	440	410	402	379
-15	318	389	434	480	481	483	470	458	423	418	386
-14	336	421	485	540	522	532	499	491	450	429	396
-13	359	485	554	606	581	585	534	520	442	447	411
-12	398	569	655	706	649	654	581	549	484	469	424
-11	466	707	777	837	753	743	632	584	501	485	436
-10	596	934	972	982	858	821	680	623	526	500	454
-9	938	1322	1231	1199	983	927	734	656	550	525	465
-8	1785	1933	1568	1394	1145	1020	792	702	567	543	476
-7	3394	2552	1845	1610	1289	1132	851	744	596	560	487
-6	4470	3044	2148	1784	1410	1229	898	781	604	578	497
-5	4857	3397	2359	1958	1533	1312	933	807	621	595	511
-4	5137	3617	2526	2062	1631	1387	986	837	640	601	518
-3	5212	3755	2638	2137	1706	1425	1020	861	650	612	523
-2	5263	3817	2710	2197	1754	1466	1036	875	658	619	525
-1	5294	3858	2738	2208	1769	1490	1051	873	665	616	526
0	5291	3845	2731	2206	1787	1485	1053	885	667	621	528

Table 10 continued

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)										
	0	1	2	3	4	5	7	9	11	13	15
1	5274	3828	2724	2200	1777	1468	1048	870	660	619	526
2	5178	3772	2670	2125	1737	1434	1028	862	654	610	527
3	5146	3684	2580	2043	1683	1388	1006	845	651	602	522
4	5008	3516	2453	1935	1592	1331	968	817	632	589	511
5	4771	3274	2258	1809	1496	1241	924	785	619	579	507
6	4361	2879	2044	1620	1375	1145	866	754	603	566	494
7	3519	2361	1759	1387	1244	1050	829	711	582	548	487
8	1762	1758	1464	1183	1103	951	771	675	565	533	478
9	892	1185	1155	995	964	840	718	642	536	516	459
10	586	880	937	837	840	755	673	595	517	495	445
11	467	673	758	711	731	680	617	570	494	480	439
12	417	536	633	623	644	607	573	541	474	455	428
13	387	471	560	542	576	557	534	498	456	442	410
14	357	411	491	485	531	509	498	472	440	422	398
15	328	382	434	443	471	463	467	453	420	411	386
16	317	349	401	415	430	430	441	427	408	398	374
17	300	330	368	376	403	412	414	407	392	377	368
18	287	312	348	362	384	387	400	388	371.8	376	351
19	283	301	327	341	362	369	377	376	364	354	344
20	273	294	319	329	340	352	359	360	356	346	341
21	266	284	306	319	325	334	349	343	342	338	328
22	266	274	300	311	317	325	341	340	333	331	327
23	260	273	293	293	309	318	325	327	321	321	319
24	-	272	292	290	298	311	321	318	318	312	307
25	-	-	284	282	291	302	313	312	308	305	304
26	-	-	275	279	285	293	305	303	310	302	299
27	-	-	274	274	284	291	295	303	297	294	293
28	-	-	275	274	281	286	293	289	295	292	290
29	-	-	270	269	275	281	290	285	289	288	289
30	-	-	262	262	266	276	283	284	289	286	285
31	-	-	-	263	269	276	280	280	280	281	277
32	-	-	-	262	265	276	282	278	278	276	278
33	-	-	-	-	265	268	278	273	275	268	276
34	-	-	-	-	261	267	266	269	271	271	273
35	-	-	-	-	262	269	269	267	269	267	269
36	-	-	-	-	-	263	263	266	273	264	264
37	-	-	-	-	-	260	261	-	266	261	267
38	-	-	-	-	-	-	265	-	266	263	262
39	-	-	-	-	-	-	-	-	265	261	261
40	-	-	-	-	-	-	-	-	-	255	263

See Table 11 for profile in short orientation and Table 12 for diagonal direction

Mean background : $241 s^{-1}$ (data not corrected)

Table 11 **Detector Profile for GP13 in Short Orientation with ^{57}Co :**
Mean Detector Response for Height (H)

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
-70	239	245	247	251	250	251	254	249	251
-65	239	244	252	255	258	257	249	250	248
-60	242	244	248	252	254	258	256	253	253
-55	236	247	252	254	255	259	257	253	257
-50	247	259	258	251	255	258	256	255	255
-45	249	255	254	260	256	260	260	263	264
-40	246	256	253	259	267	266	270	269	267
-35	249	255	264	269	268	275	276	277	278
-30	257	263	268	280	277	285	290	289	286
-25	266	270	276	296	288	303	311	315	306
-20	278	284	301	324	336	342	347	340	347
-18	287	305	321	341	356	368	373	371	354
-16	299	326	347	375	509	404	403	389	371
-14	322	341	386	413	434	449	450	427	395
-12	349	404	450	493	509	518	496	467	416
-10	395	477	554	608	613	622	569	499	434
-9	422	540	633	689	699	688	597	531	455
-8	465	646	746	802	785	765	651	554	461
-7	525	764	897	950	903	874	699	581	469
-6	596	989	1121	1138	1038	970	769	606	486
-5	691	1366	1436	1361	1205	1088	810	620	504
-4	1341	2023	1860	1609	1383	1231	854	652	500
-3	3419	2752	2250	1879	1548	1327	905	663	505
-2	4682	3426	2615	2113	1702	1429	932	678	506
-1	5245	3835	2875	2279	1809	1509	951	691	509
0	5411	3947	2979	2317	1851	1528	948	683	510
1	5416	3847	2947	2284	1831	1498	949	689	502
2	5128	3506	2720	2153	1768	1454	931	679	501
3	4100	2848	2370	1913	1624	1368	904	662	499
4	1510	2064	1966	1644	1461	1259	862	653	496

continued

Table 11 continued

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
5	734	1400	1498	1393	1264	1131	807	624	486
6	604	999	1173	1145	1077	1006	760	610	473
7	533	772	935	945	941	882	710	570	462
8	482	627	768	804	826	780	668	548	449
9	435	541	643	691	712	704	613	533	442
10	402	482	568	610	639	641	579	507	432
12	355	382	458	491	521	529	508	462	411
14	325	351	393	423	446	451	452	426	386
16	298	319	346	368	387	404	407	393	367
18	293	297	320	341	350	363	375	364	346
20	281	290	302	325	328	345	352	347	338
25	268	267	279	287	296	300	313	305	303
30	252	257	263	267	282	286	284	290	293
35	245	255	258	263	272	268	269	281	278
40	248	255	255	263	263	265	261	267	271
45	249	246	257	258	264	261	262	256	265
50	244	245	251	255	268	260	262	254	255
55	244	251	253	255	259	253	251	250	251
60	242	245	257	253	256	255	252	251	249
65	245	250	249	250	251	255	251	247	246
70	243	245	242	249	254	249	249	249	249

Mean background : 236 s^{-1} (data not corrected)

Table 12 **Detector Profile for GP13 in Diagonal Direction with ^{57}Co :**
Mean Detector Response for a Height of 1 cm

Distance from Origin (cm)	Mean Detector Response (s^{-1})
-40	254
-39	251
-38	252
-37	254
-36	252
-35	255
-34	257
-33	259
-32	252
-31	255
-30	257
-29	263
-28	263
-27	260
-26	266
-25	266
-24	270
-23	273
-22	279
-21	278
-20	283
-19	292
-18	295
-17	310
-16	320
-15	339
-14	366

Distance from Origin (cm)	Mean Detector Response (s^{-1})
-13	408
-12	466
-11	571
-10	741
-9	1046
-8	1523
-7	2032
-6	2536
-5	2989
-4	3352
-3	3645
-2	3743
-1	3838
0	3877
1	3816
2	3708
3	3556
4	3254
5	2961
6	2573
7	2030
8	1377
9	940
10	658
11	519
12	438
13	386

Distance from Origin (cm)	Mean Detector Response (s^{-1})
14	349
15	336
16	317
17	304
18	300
19	286
20	284
21	277
22	274
23	270
24	267
25	261
26	260
27	258
28	261
29	256
30	256
31	256
32	258
33	254
34	253
35	249
36	250
37	249
38	248
39	249
40	247

Mean background : 242 s^{-1} (data not corrected)

Table 13 **Detector Profile for GP13 with ¹³⁷Cs : Mean Detector Response for Height (H)**

Distance from Origin (cm)	Mean Detector Response (s ⁻¹) at Height H (cm)										
	0	1	2	3	4	5	7	9	11	13	15
-26	-	-	-	-	-	-	254	-	-	-	-
-25	-	-	-	-	-	-	255	-	251	-	-
-24	-	-	-	-	-	-	255	-	252	-	-
-23	245	-	253	-	253	-	256	-	250	-	-
-22	240	247	255	252	259	256	256	-	251	250	245
-21	248	252	260	261	260	256	256	254	255	250	250
-20	251	246	259	263	264	264	264	255	257	251	251
-19	257	252	265	264	268	267	263	261	260	261	249
-18	256	255	265	273	269	271	270	267	262	260	253
-17	259	263	269	279	277	273	275	260	269	261	257
-16	269	269	273	282	281	279	281	270	270	263	256
-15	272	273	284	290	286	286	284	276	271	265	256
-14	280	280	292	295	297	292	291	278	277	264	263
-13	287	290	308	309	307	300	294	281	278	272	263
-12	303	303	322	322	315	309	302	289	282	267	261
-11	324	333	348	340	333	320	311	291	291	270	263
-10	369	370	384	367	353	331	322	300	294	275	265
-9	443	440	435	403	376	348	337	304	295	278	263
-8	640	554	499	430	400	366	342	314	304	285	268
-7	860	712	568	470	421	375	357	317	304	287	269
-6	1019	827	622	486	438	388	368	325	308	282	274
-5	1099	902	671	518	468	406	370	329	313	285	273
-4	1139	940	697	534	484	409	379	331	315	288	277
-3	1160	973	724	552	489	415	388	334	315	293	277
-2	1179	989	733	563	493	429	383	337	317	293	274
-1	1190	1002	737	565	502	421	391	335	319	290	279
0	1192	1001	738	563	500	429	392	340	312	291	272
1	1189	998	735	555	501	427	388	339	314	286	279
2	1186	986	720	554	493	422	379	333	317	289	273
3	1153	971	708	538	490	412	378	334	311	291	273
4	1130	947	676	523	477	402	374	322	307	288	274
5	1078	886	648	505	459	389	361	323	303	280	267
6	1018	833	607	471	441	382	355	323	302	281	272
7	889	714	542	440	422	364	341	312	298	280	270

continued

Table 13 continued

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)										
	0	1	2	3	4	5	7	9	11	13	15
8	646	588	481	408	395	351	337	303	293	279	268
9	427	450	408	379	363	339	322	302	292	273	266
10	364	380	367	358	345	323	314	293	285	274	267
11	330	335	334	335	328	313	302	288	281	272	264
12	306	311	316	317	312	299	298	278	277	268	257
13	289	295	303	304	301	298	284	279	273	265	261
14	275	284	295	290	293	288	287	280	270	263	258
15	271	274	283	284	284	279	276	270	271	260	255
16	268	266	277	278	276	278	274	269	264	260	254
17	266	265	271	270	268	271	267	261	263	256	257
18	257	261	263	268	269	267	259	257	262	256	251
19	256	258	264	265	265	264	260	259	259	250	251
20	248	255	255	258	265	256	260	254	258	252	244
21	247	252	255	257	260	262	256	253	251	253	249
22	246	247	248	253	255	258	253	-	255	246	242
23	-	-	-	-	255	250	251	-	246	-	-

See Table 14 for profile in short orientation.

Mean background : $236 s^{-1}$ (data not corrected)

Table 14 **Detector Profile for GP13 in Short Orientation with ^{137}Cs :**
Mean Detector Response for Height (H)

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
-70	250	249	256	253	244	251	251	244	242
-65	246	250	251	253	250	253	256	242	239
-60	246	246	251	248	256	253	247	246	246
-55	250	254	252	255	252	253	254	251	247
-50	250	255	247	259	257	256	254	245	248
-45	249	245	255	249	252	257	255	251	246
-40	247	253	253	255	254	258	251	259	250
-35	244	256	254	261	255	261	259	258	246
-30	250	257	259	259	259	264	257	261	255
-25	255	256	261	261	263	264	266	259	257
-20	262	273	275	271	264	276	267	268	256
-18	258	271	275	279	278	283	278	268	266
-16	271	281	282	284	288	292	279	271	269
-14	278	287	295	298	297	300	289	277	274
-12	291	296	306	312	308	311	295	283	273
-10	309	326	326	334	330	326	302	292	282
-9	326	350	347	343	338	335	313	289	281
-8	345	376	364	374	356	353	323	299	278
-7	368	408	390	398	378	368	328	299	284
-6	411	453	425	418	398	384	336	310	286
-5	494	525	484	457	425	405	348	312	290
-4	680	626	543	504	455	421	351	324	291
-3	977	745	599	535	474	444	360	322	291
-2	1169	831	660	582	504	463	370	327	290
-1	1266	882	702	593	514	467	368	325	288
0	1301	898	725	607	523	474	367	323	292
1	1268	885	714	600	518	474	370	324	282
2	1181	827	680	582	508	460	368	318	296
3	966	729	631	544	481	444	365	320	291
4	687	597	571	516	465	434	355	317	286
5	489	498	497	463	431	404	344	316	287
6	406	428	457	430	416	389	342	313	279
7	368	388	405	394	376	372	329	307	280
8	342	353	374	376	365	356	324	302	278

Table 14 continued

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
9	324	332	354	355	339	344	317	290	282
10	312	318	331	339	325	330	319	293	281
12	288	299	309	313	311	307	304	294	275
14	280	283	295	302	295	300	286	278	271
16	273	279	288	284	281	287	281	278	264
18	263	270	273	277	281	280	278	269	260
20	265	267	269	275	272	275	275	263	259
25	256	256	267	256	263	263	265	254	251
30	249	254	259	259	255	257	261	254	254
35	249	250	258	257	254	256	259	251	251
40	249	243	251	255	248	253	250	247	243
45	247	251	258	257	249	255	251	251	245
50	249	243	254	256	250	256	252	251	242
55	247	251	249	251	246	249	250	242	239
60	243	244	253	236	249	244	246	248	246
65	243	244	257	244	248	249	245	248	237
70	246	246	251	236	246	244	249	244	242

Mean background : 243 s^{-1} (data not corrected)

Table 15 **Detector Profile for G2 with ^{57}Co : Mean Detector Response for Height (H)**

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
-70	-	-	-	-	-	-	-	-	419
-65	-	-	-	-	-	-	426	413	423
-60	-	-	-	-	-	-	426	401	427
-55	-	-	-	-	-	-	444	427	408
-50	-	-	-	-	-	422	451	438	445
-48	-	-	-	-	-	424	446	436	-
-46	-	-	-	-	-	424	446	438	-
-45	-	-	-	-	-	-	-	-	446
-44	-	-	-	419	419	434	446	446	-
-42	-	-	-	428	424	445	452	451	-
-40	-	-	-	433	423	423	459	448	460
-38	-	-	440	435	422	433	462	462	455
-37.5	-	-	437	-	-	-	-	-	-
-37	-	-	443	-	-	-	-	-	-
-36.5	-	-	432	-	-	-	-	-	-
-36	-	-	448	447	424	445	458	457	455
-35.5	-	-	444	-	-	-	-	-	-
-35	-	-	443	-	-	-	-	-	-
-34.5	-	-	446	-	-	-	-	-	-
-34	-	-	450	445	427	460	469	455	464
-33.5	-	-	450	-	-	-	-	-	-
-33	443	443	453	-	-	-	-	-	-
-32.5	439	437	452	-	-	-	-	-	-
-32	448	448	458	451	430	464	473	468	471
-31.5	445	453	456	-	-	-	-	-	-
-31	447	452	460	-	-	-	-	-	-
-30.5	452	456	457	-	-	-	-	-	-
-30	451	456	462	461	443	465	484	470	477
-29.5	448	458	463	-	-	-	-	-	-
-29	449	461	468	-	-	-	-	-	-
-28.5	459	461	470	-	-	-	-	-	-
-28	462	457	472	473	453	472	480	476	477
-27.5	464	463	474	-	-	-	-	-	-
-27	466	465	474	-	-	-	-	-	-
-26.5	466	471	474	-	-	-	-	-	-

Table 15 continued

Distance from origin (cm)	Mean Detector Response (s ⁻¹) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
-26	470	467	478	482	465	489	499	486	484
-25.5	473	468	481	-	-	-	-	-	-
-25	474	474	485	-	-	-	-	-	-
-24.5	474	477	486	-	-	-	-	-	-
-24	478	481	495	486	471	496	488	487	490
-23.5	473	484	496	-	-	-	-	-	-
-23	478	491	498	-	-	-	-	-	-
-22.5	487	490	503	-	-	-	-	-	-
-22	493	501	506	503	494	519	519	504	492
-21.5	499	504	514	-	-	-	-	-	-
-21	500	510	518	-	-	-	-	-	-
-20.5	502	512	517	-	-	-	-	-	-
-20	508	519	528	524	508	528	532	519	499
-19.5	516	526	531	-	-	-	-	-	-
-19	518	531	539	-	-	-	-	-	-
-18.5	528	536	547	-	-	-	-	-	-
-18	533	545	553	559	525	550	545	534	513
-17.5	548	554	562	-	-	-	-	-	-
-17	551	568	578	-	-	-	-	-	-
-16.5	559	578	586	-	-	-	-	-	-
-16	565	584	586	579	554	585	574	544	511
-15.5	578	588	604	-	-	-	-	-	-
-15	591	601	613	-	-	-	-	-	-
-14.5	610	625	625	-	-	-	-	-	-
-14	622	635	638	635	601	627	606	561	518
-13.5	641	644	657	-	-	-	-	-	-
-13	651	674	674	-	-	-	-	-	-
-12.5	673	688	691	-	-	-	-	-	-
-12	703	712	711	696	665	677	625	579	536
-11.5	734	748	739	-	-	-	-	-	-
-11	749	765	759	-	-	-	-	-	-
-10.5	786	802	780	-	-	-	-	-	-
-10	826	836	820	785	741	749	669	605	544
-9.5	884	885	856	802	752	766	686	607	540
-9	912	914	894	841	790	782	691	607	557
-8.5	965	977	939	877	822	823	705	617	554
-8	1031	1026	982	935	849	840	710	619	553
-7.5	1108	1088	1036	970	889	861	734	620	559

Table 15 continued

Distance from origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
-7	1202	1161	1088	995	929	892	748	626	554
-6.5	1289	1241	1146	1057	955	909	747	636	550
-6	1406	1343	1219	1125	992	940	764	636	560
-5.5	1555	1469	1317	1192	1047	975	782	651	560
-5	1711	1597	1407	1247	1090	1015	790	651	563
-4.5	1941	1765	1534	1330	1135	1051	800	654	553
-4	2178	1936	1702	1407	1205	1096	808	653	564
-3.5	2617	2223	1865	1530	1267	1145	821	651	561
-3	3043	2667	2072	1661	1364	1174	829	654	568
-2.5	4392	3122	2350	1783	1430	1228	843	658	567
-2	5898	3866	2664	1977	1517	1267	858	670	568
-1.5	6937	4475	2913	2091	1580	1308	867	664	564
-1	7615	4872	3134	2221	1669	1340	873	674	518
-0.5	7897	5123	3285	2316	1708	1360	867	677	576
0	7958	5146	3295	2337	1719	1341	868	672	576
0.5	7912	5049	3243	2311	1697	1349	858	677	570
1	7721	4744	3087	2222	1667	1322	855	674	568
1.5	7199	4294	2834	2084	1599	1265	846	676	568
2	6182	3736	2531	1968	1514	1227	835	656	570
2.5	4591	3018	2225	1823	1418	1177	829	666	556
3	3208	2482	1977	1664	1344	1125	812	650	565
3.5	2621	2152	1782	1532	1285	1090	797	652	567
4	2301	1894	1628	1450	1214	1071	785	655	565
4.5	2010	1717	1516	1352	1156	1016	774	649	563
5	1762	1558	1396	1277	1107	981	784	654	563
5.5	1587	1421	1306	1211	1057	958	750	647	566
6	1450	1292	1209	1132	1013	939	748	642	567
6.5	1297	1220	1133	1070	955	909	734	632	557
7	1211	1136	1063	1015	925	873	719	628	551
7.5	1118	1068	1005	962	891	841	709	623	556
8	1047	999	943	922	851	819	691	613	550
8.5	991	945	907	888	819	799	685	612	557
9	917	882	858	855	778	768	677	611	555
9.5	878	851	828	819	783	750	662	601	545
10	824	807	799	786	739	722	635	599	540
10.5	774	771	771	-	-	-	-	-	-
11	739	748	746	-	-	-	-	-	-
11.5	717	719	717	-	-	-	-	-	-

Table 15 continued

Distance from origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
12	692	695	700	704	667	654	618	581	540
12.5	674	687	678	-	-	-	-	-	-
13	658	670	662	-	-	-	-	-	-
13.5	643	651	648	-	-	-	-	-	-
14	623	644	636	636	607	615	581	550	528
14.5	603	615	622	-	-	-	-	-	-
15	589	598	599	-	-	-	-	-	-
15.5	582	592	597	-	-	-	-	-	-
16	565	577	585	587	566	581	563	541	513
16.5	558	573	568	-	-	-	-	-	-
17	545	560	563	-	-	-	-	-	-
17.5	536	549	547	-	-	-	-	-	-
18	531	550	546	551	519	550	542	521	510
18.5	522	530	532	-	-	-	-	-	-
19	515	522	533	-	-	-	-	-	-
19.5	509	520	529	-	-	-	-	-	-
20	504	513	525	519	502	531	523	509	499
20.5	499	510	517	-	-	-	-	-	-
21	499	505	509	-	-	-	-	-	-
21.5	493	498	507	-	-	-	-	-	-
22	486	490	500	504	492	509	504	499	494
22.5	483	493	494	-	-	-	-	-	-
23	478	491	492	-	-	-	-	-	-
23.5	480	480	-	-	-	-	-	-	-
24	477	477	-	496	471	496	497	488	489
24.5	474	482	-	-	-	-	-	-	-
25	465	481	478	-	-	-	-	-	-
25.5	469	465	-	-	-	-	-	-	-
26	465	470	-	484	467	487	488	481	475
26.5	461	465	-	-	-	-	-	-	-
27	459	465	463	-	-	-	-	-	-
27.5	455	466	-	-	-	-	-	-	-
28	458	465	-	472	460	476	477	471	479
28.5	452	455	-	-	-	-	-	-	-
29	453	459	468	-	-	-	-	-	-
29.5	453	454	-	-	-	-	-	-	-
30	447	453	-	462	450	475	475	466	468

Table 15 continued

Distance from origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
30.5	448	451	-	-	-	-	-	-	-
31	450	455	456	-	-	-	-	-	-
31.5	442	446	-	-	-	-	-	-	-
32	449	434	-	463	453	468	464	470	467
32.5	444	429	-	-	-	-	-	-	-
33	439	-	448	-	-	-	-	-	-
34	-	-	-	455	434	467	463	460	463
35	-	-	449	-	-	-	-	-	-
36	-	-	-	451	429	461	461	455	455
37	-	-	434	-	-	-	-	-	-
38	-	-	-	451	434	457	456	451	448
39	-	-	438	-	-	-	-	-	-
40	-	-	-	434	432	441	443	436	454
41	-	-	436	-	-	-	-	-	-
42	-	-	-	441	420	448	446	441	-
44	-	-	-	430	431	442	437	454	-
45	-	-	-	-	-	-	-	-	445
46	-	-	-	436	422	438	446	438	-
48	-	-	-	-	-	449	445	444	-
50	-	-	-	-	-	442	429	442	442
52	-	-	-	-	-	441	-	-	-
54	-	-	-	-	-	433	-	-	-
55	-	-	-	-	-	-	439	430	443
56	-	-	-	-	-	434	-	-	-
58	-	-	-	-	-	438	-	-	-
60	-	-	-	-	-	-	433	437	441
64	-	-	-	-	-	420	-	-	-
65	-	-	-	-	-	-	421	433	436
69	-	-	-	-	-	-	-	424	-
70	-	-	-	-	-	-	-	-	434

Mean background : $466 s^{-1}$ (data not corrected)

Table 16 **Detector Profile for G2 with ^{137}Cs : Mean Detector Response for Height (H)**

Distance from Origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
-70	-	436	406	406	428	431	438	429	433
-65	-	423	390	417	430	432	438	427	435
-60	-	423	381	399	428	425	433	434	438
-55	419	419	396	423	428	442	430	439	441
-50	425	432	391	418	436	436	445	436	439
-46	427	435	389	-	-	-	-	-	-
-45	-	-	-	415	431	440	438	441	434
-42	441	434	421	-	-	-	-	-	-
-40	-	-	-	409	444	443	451	452	449
-38	431	444	438	-	-	-	-	-	-
-35	-	-	-	424	452	458	455	455	454
-34	445	442	447	-	-	-	-	-	-
-30	449	454	456	444	465	467	460	455	455
-28	459	465	458	-	-	-	-	-	-
-26	469	470	468	-	-	-	-	-	-
-25	-	-	-	461	472	484	480	471	466
-24	469	483	483	-	-	-	-	-	-
-22	484	495	493	-	-	-	-	-	-
-20	501	507	497	503	497	505	508	489	473
-18	511	526	519	521	520	512	505	500	480
-16	543	555	542	545	540	540	523	510	484
-14	587	594	583	590	564	563	546	518	489
-12	633	641	630	627	614	605	567	529	505
-10	720	715	706	684	660	646	589	544	510
-9.5	759	759	722	715	674	655	606	554	508
-9	800	780	768	729	707	658	611	558	508
-8.5	842	813	790	755	722	700	618	542	492
-8	877	858	824	779	747	724	637	563	523
-7.5	928	885	856	809	761	737	638	566	515
-7	999	941	901	842	786	740	628	576	524
-6.5	1077	1002	968	871	809	759	656	580	523
-6	1167	1072	1013	927	844	793	661	576	525
-5.5	1281	1170	1071	972	883	810	676	581	526
-5	1405	1277	1151	1018	903	838	676	590	531
-4.5	1601	1403	1232	1091	938	864	684	581	527

continued

Table 16 continued

Distance from origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
-4	1804	1533	1335	1149	972	868	695	588	527
-3.5	2133	1698	1416	1212	1009	898	698	592	518
-3	2548	1911	1571	1261	1051	926	697	590	536
-2.5	3243	2160	1700	1334	1090	942	699	600	533
-2	3852	2467	1815	1380	1142	962	706	600	531
-1.5	4412	2679	1936	1449	1168	981	714	600	531
-1	4855	2885	2020	1488	1185	997	723	604	540
-0.5	5047	2992	2052	1525	1209	1000	719	604	534
0	5146	3011	2060	1522	1197	995	718	606	536
0.5	5112	2993	2042	1491	1208	988	722	593	524
1	4888	2892	1948	1475	1179	958	721	600	530
1.5	4538	2705	1867	1406	1163	958	715	603	527
2	3916	2448	1723	1352	1128	942	709	597	488
2.5	3055	2181	1592	1284	1093	920	684	594	527
3	2398	1886	1465	1214	1042	907	690	592	529
3.5	2049	1724	1362	1156	1015	879	690	591	524
4	1811	1540	1257	1095	973	843	684	583	529
4.5	1553	1395	1172	1031	938	829	673	588	519
5	1394	1274	1100	978	901	811	670	573	525
5.5	1265	1166	1034	930	868	786	662	579	522
6	1150	1094	994	892	842	755	640	571	512
6.5	1070	1020	926	867	809	741	626	566	512
7	995	952	875	818	786	730	637	568	522
7.5	910	893	831	798	756	705	622	555	514
8	852	847	803	763	739	685	610	550	525
8.5	825	815	774	721	709	655	604	557	501
9	785	767	740	710	697	660	601	550	511
9.5	746	742	709	696	666	657	590	547	511
10	716	705	702	663	666	632	571	546	511
12	629	634	613	608	614	584	554	529	500
14	591	580	574	577	576	565	538	514	495
16	537	547	540	537	540	534	507	500	487
18	512	525	522	516	516	517	506	488	485
20	497	505	501	505	502	498	491	485	466
22	476	489	487	-	-	-	-	-	-
24	475	474	481	-	-	-	-	-	-
25	-	-	-	473	474	472	472	449	462
26	460	468	470	-	-	-	-	-	-

continued

Table 16 continued

Distance from origin (cm)	Mean Detector Response (s^{-1}) at Height H (cm)								
	0	1	2	3	4	5	8	11	15
28	467	453	468	-	-	-	-	-	-
30	456	432	447	457	461	463	465	464	450
34	450	440	450	-	-	-	-	-	-
35	-	-	-	450	445	458	457	449	451
38	442	401	434	-	-	-	-	-	-
40	-	-	-	443	440	439	440	434	-
42	437	443	442	-	-	-	-	-	439
45	-	-	-	428	437	433	436	435	443
46	442	440	441	-	-	-	-	-	-
50	435	437	442	439	432	429	436	412	434
55	429	432	422	428	429	439	435	416	437
60	428	428	425	429	439	432	430	426	432
65	432	425	428	409	431	428	432	425	418
70	420	427	417	421	427	427	428	423	426

Mean background : 410 s^{-1} (data not corrected)

Table 17**Data for Annular Plot : DP2 with ^{234}U**

Horizontal Distance (cm)	Mean Response (cps)	Area	Area x cps	Running Total	% increase	Percentage Detector Response
0	175	1	175	175	-	2
1	175	8	1400	1575	800	17
2	181	16	2896	4471	184	49
3	147	24	3528	7999	79	87
4	30	32	960	8959	12	97
5	1.5	40	60	9019	0.7	98.0
6	0.6	48	28.8	9047.8	0.3	98.3
7	0.3	56	16.8	9064.6	0.2	98.5
8	0.1	64	6.4	9071	0.1	98.6
9	0.35	72	25.2	9096.2	0.3	98.9
10	0.35	80	28	9124.2	0.3	99.2

Estimated maximum response equals 9200 cps

Table 18

Summary of Detector Profile Results

Probe + Source	Minimum radial distances (cm) necessary to achieve various percentages of the estimated semi-infinite-plane response at a source-detector separation of 1 cm		
	90%	95%	99%
EP15 + ^{241}Am	2.5	3	3
EP15 + ^{234}U	2.5	3	4.5
DP2 + ^{241}Am	4	4	4
DP2 + ^{234}U	3.5	4	10
DP2 + $^{90}\text{Sr}/^{90}\text{Y}$	6	7	15
GP13 + ^{57}Co	20	29	>40*
GP13 + ^{137}Cs	19	22	>22*
G2 + ^{57}Co	17	20	24
G2 + ^{137}Cs	>30*	>30*	>30*

* Where the > symbol is displayed, the detector profiles were not studied to great enough radial distances to enable an accurate determination of the required minimum radial distance to be determined.

Table 19 Effects of Backscatter from ^{234}U Large Area Source with the EP15 Probe

Detector	Source - Detector Distance (mm)	Backing Plate Thickness (mm)	Mean Observed Countrate (cps) *	Change in Response
EP15	0	3	$24.8 \pm 12.4 \%$	-
		6	$25.2 \pm 12.3 \%$	+ 1.6 %
		9	$24.8 \pm 12.4 \%$	0
		12	$25.0 \pm 12.0 \%$	+ 0.8 %
	3	3	$19.7 \pm 19.3 \%$	-
		6	$18.0 \pm 18.7 \%$	- 8.6 %
		9	$19.0 \pm 20.2 \%$	- 3.6 %
		12	$15.8 \pm 16.3 \%$	-19.8 %
	10	3	$4.7 \pm 46.8 \%$	-
		6	$5.0 \pm 41.0 \%$	+ 6.4 %
		9	$4.8 \pm 44.5 \%$	+ 2.1 %
		12	$3.5 \pm 41.7 \%$	- 25.5 %

* Data has not been background corrected (1.2 s^{-1}). Uncertainties are quoted are at the 1σ level.

Table 20 **Effects of Backscatter from $^{90}\text{Sr}/^{90}\text{Y}$ Large Area Source with the DP2 Probe**

Detector	Source - Detector Distance (mm)	Backing Plate Thickness (mm)	Mean Observed Countrate (cps) *	Change in Response
DP2	0	3	$1635 \pm 0.5 \%$	-
		6	$1651 \pm 0.5 \%$	+ 1.0 %
		9	$1651 \pm 0.4 \%$	+ 1.0 %
		12	$1661 \pm 0.6 \%$	+ 1.6 %
	3	3	$1672 \pm 0.4 \%$	-
		6	$1650 \pm 0.2 \%$	- 1.3 %
		9	$1660 \pm 0.5 \%$	- 0.7 %
		12	$1664 \pm 0.2 \%$	- 0.5 %
	10	3	$1478 \pm 0.4 \%$	-
		6	$1503 \pm 0.5 \%$	+ 1.7 %
		9	$1508 \pm 0.7 \%$	+ 2.0 %
		12	$1521 \pm 0.4 \%$	+ 2.9 %

* Data has not been background corrected (6.3 s^{-1}) Uncertainties are quoted are at the 1σ level.

Table 21 Effects of Backscatter from ^{57}Co large area source

Detector	Source-Detector distance (mm)	Backing plate Thickness (mm)	Mean Value observed (cps)	Increase in Response(%)
GP13	0	3	4548	-
		6	4651	2.3
		9	4747	4.4
		12	4787	5.3
	3	3	4422	-
		6	4536	2.6
		9	4548	2.8
		12	4665	5.5
	10	3	3648	-
		6	3733	2.3
		9	3810	4.4
		12	3846	5.4
G2	0	3	3898	-
		6	3953	1.4
		9	3973	1.9
		12	4005	2.7
	3	3	3475	-
		6	3597	3.5
		9	3650	5.0
		12	3691	6.2
	10	3	2862	-
		6	2918	2.0
		9	2938	2.7
		12	2978	4.1

Table 22 Effects of Backscatter from ^{137}Cs large area source

Detector	Source-Detector distance (mm)	Backing plate Thickness (mm)	Mean Value observed (cps)	Increase in Response (%)
GP13	0	3	550	-
		6	562	2.2
		9	581	5.6
		12	602	9.5
	3	3	507	-
		6	533	5.1
		9	543	7.1
		12	556	9.7
	10	3	444	-
		6	453	2.0
		9	468	5.4
		12	468	5.4
G2	0	3	1298	-
		6	1324	2.0
		9	1342	3.4
		12	1358	4.6
	3	3	1221	-
		6	1222	0.1
		9	1223	0.2
		12	1230	0.7
	10	3	991	-
		6	1024	3.3
		9	1029	3.8
		12	1040	5.0

Uncertainties are quoted at the 1σ level.

Table 23 Results of Edge Effects Study

Source	Detector	Mean Background (cps)	Source - Detector Distance (mm)	Mean Detector Response (cps)†	
				Without Edge Plate	With Edge Plate
²⁴¹ Am	EP15	1.3	0	246 ± 14.4	238 ± 7.2
			3	205 ± 7.2	197 ± 14.4
			10	135 ± 7.3	125 ± 11.5
²⁴¹ Am	DP2	4.9	0	684 ± 5.3	677 ± 2.8
			3	614 ± 2.6	623 ± 6.4
			10	456 ± 0.6	450 ± 1.4
²³⁴ U	EP15	1.3	0	10.8 ± 2.3	10 ± 2.0
			3	7.6 ± 2.1	7.3 ± 1.7
			10	2.1 ± 0.9	1.8 ± 0.6
²³⁴ U	DP2	4.9	0	40.9 ± 0.6	42.1 ± 0.6
			3	34.4 ± 1.1	33.4 ± 2.0
			10	15.9 ± 1.0	17.6 ± 1.4
¹⁴ C	DP2	13.6	0	67.6 ± 1.4	67.4 ± 1.4
			3	61.4 ± 0.9	61.3 ± 0.4
			10	51.1 ± 2.8	50.6 ± 1.2
⁹⁰ Sr	DP2	7.9	0	801 ± 0.9	796 ± 6.9
			3	784 ± 2.9	812 ± 5.2
			10	754 ± 6.9	755 ± 6.1
⁵⁷ Co	GP13 (long)*	251	0	3491 ± 10.6	3461 ± 6.6
			3	3272 ± 1.4	3277 ± 5.5
			10	2940 ± 13.3	2934 ± 6.9
⁵⁷ Co	GP13 (short)*	251	0	2625 ± 3.8	2628 ± 0.9
			3	2563 ± 11.5	2594 ± 6.9
			10	2340 ± 4.6	2344 ± 5.5
⁵⁷ Co	G2	403.8	0	2446 ± 9.5	2450 ± 2.3
			3	2252 ± 11.8	2284 ± 6.4
			10	2001 ± 6.1	2004 ± 4.9
⁵⁷ Co	EP15	1.1	0	3.5 ± 0.9	3.5 ± 0.9
			3	3.8 ± 0.9	5 ± 0.9
			10	3.5 ± 0.6	4 ± 0.9
¹³⁷ Cs	GP13 (long)*	251	0	473 ± 2.3	476 ± 3.4
			3	451 ± 2.3	459 ± 0.9
			10	407 ± 6.1	409 ± 1.4
¹³⁷ Cs	GP13 (short)*	251	0	423 ± 4.6	419 ± 3.2
			3	399 ± 1.7	415 ± 1.4
			10	377 ± 1.2	370 ± 4.3
¹³⁷ Cs	G2	403.8	0	911 ± 5.2	902 ± 8.4
			3	846 ± 4.0	852 ± 5.2
			10	770 ± 9.5	775 ± 5.8

* Refers to probe orientation, see figure 4

† Data is not background corrected. Uncertainties are quoted at the 1σ (68% confidence) level.

Table 24 Effects of Rimmed Calibration Sources

Rim Width (mm)	Mean Detector Response * (cps)
0	3.4 ± 1.3
5	3.3 ± 1.5
10	3.5 ± 1.7

* Data has not been background corrected (1.3 cps).
 The uncertainties quoted are standard deviations at 1σ .

Measurements were made with the EP15 detector and ^{57}Co source in contact (ie. at a height of 0cm).

Table 25 Summary of Field Trial Results for Am-241 + EP15 Probe : Detector Responses Observed (cps)

Source Orientation	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Mean	Standard Deviation (%)	Spread (%)
Normal	515.3	473.3	570.1	496.2	476.0	506.2	7.8	19.1
Low Case	437.4	408.3	460.1	401.1	445.3	430.4	5.8	13.7
Centre	458.8	417.4	439.1	399.6	421.4	427.3	5.3	13.7

Table 26 Summary of Field Trial Results for U-234 + EP15 Probe : Detector Responses Observed (cps)

Source Orientation	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Mean	Standard Deviation (%)	Spread (%)
Normal	22.1	21.2	23.6	23.1	20.3	22.1	6.8	15.0
High Case	32.2	33.0	42.4	31.1	31.3	34.0	14.1	33.2
Low Case	19.9	17.4	21.4	19.9	17.3	19.2	9.4	21.4
Centre	22.7	21.4	24.3	22.3	21.7	22.5	4.9	12.9

Table 27 Summary of Field Trial Results for Am-241 + DP2 Probe : Detector Responses Observed (cps)

Source Orientation	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Mean	Standard Deviation (%)	Spread (%)	*Mean	*Standard Deviation (%)	*Spread (%)
Normal	1396	1471	1325	1429	1415	1407	3.8	10.4	1428	2.2	5.2
High Case	1430	1505	1350	1443	1408	1427	7.9	10.8	1446	2.9	6.7
Low Case	1273	1345	1197	1284	1320	1284	4.4	11.5	1306	2.5	5.6
Centre	-	1396	1259	1336	1344	1334	3.7	10.3	1359	2.0	4.4

* results excluding Lab 3 values

Table 28 Summary of Field Trial Results for U-234 + DP2 Probe : Detector Responses Observed (cps)

Source Orientation	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Mean	Standard Deviation (%)	Spread (%)
Normal	83.7	80.5	73.8	87.6	85.7	82.3	6.5	16.8
High Case	101.9	88.8	102.0	102.3	101.0	99.2	5.9	13.6
Low Case	71.6	69.7	60.0	78.5	70.4	70.0	9.5	26.4
Centre	83.3	82.8	74.4	83.0	87.1	82.1	5.7	15.5

Table 29 Summary of Field Trial Results for Sr-90/ Y-90 + DP2 Probe : Detector Responses Observed (cps)

Source Orientation	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Mean	Standard Deviation (%)	Spread (%)
Normal	1787	1655	1768	1662	1781	1731	3.8	7.6
High Case	1966	1821	1924	1811	1916	1888	3.6	8.2
Low Case	1344	1273	1364	1262	1407	1330	4.6	10.9
Centre	1636	1540	1603	1533	1639	1590	3.2	6.7

Table 30 Summary of Field Trial Results for C-14 + BP7 Probe : Detector Responses Observed (cps)

Source Orientation	*Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Mean	Standard Deviation (%)	Spread (%)
Normal	-	461.9	480.0	495.0	484.4	480.3	2.9	6.9
High Case	-	580.4	502.0	513.4	465.4	515.3	9.3	22.3
Low Case	-	377.7	365.0	359.2	358.8	365.2	2.4	5.2
Centre	-	531.8	489.0	499.6	481.8	500.6	4.4	10.0

* measurements not made

Table 31 Summary of Field Trial Results for Co-57 + GP13 Probe : Detector Responses Observed (cps)

Source Orientation	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Mean	Standard Deviation (%)	Spread (%)	*Mean	*Standard Deviation (%)	*Spread (%)
Normal	5940	5792	6059	6058	5919	5954	1.9	4.5	5994	1.3	2.4

* results excluding Lab 2 results

Table 32 Summary of Field Trial Results for Cs-137 + GP13 Probe : Detector Responses Observed (cps)

Source Orientation	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Mean	Standard Deviation (%)	Spread (%)	*Mean	*Standard Deviation (%)	*Spread (%)
Normal	533.7	702.9	602.2	572.5	555.8	597.4	11.1	28.3	566.0	5.1	12.1

* results excluding Lab 2 value

Table 33 Summary of Field Trial Results for Co-57 + G2 Probe : Detector Responses Observed (cps)

Source Orientation	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Mean	Standard Deviation (%)	Spread (%)	*Mean	*Standard Deviation (%)	*Spread (%)
Normal	4352	4399	4319	4345	4363	4355	0.7	1.8	4345	0.5	1.1
Centre	2700	2726	2530	2642	2636	2647	2.9	7.4	2627	2.7	6.5

* results excluding Lab 2 values

Table 34 Summary of Field Trial Results for Cs-137 + G2 Probe : Detector Responses Observed (cps)

Source Orientation	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Mean	Standard Deviation (%)	Spread (%)	*Mean	*Standard Deviation (%)	*Spread (%)
Normal	1292	1461	1253	1323	1306	1327	6.0	15.7	1293	2.3	5.4
Centre	864.9	947.2	785.9	836.9	858.1	858.6	6.8	18.8	836.5	4.3	9.4

* results excluding Lab 2 values

Table 35 Measurements Performed on the Very Large Area Source

Source Orientation	Observed Detector Responses (cps) †
0°	466 ± 4 472 ± 4 467 ± 4
90°	460 ± 4 459 ± 4 453 ± 4
180°	461 ± 4 464 ± 4 462 ± 4
270°	465 ± 4 462 ± 4 457 ± 4
Mean Response	462 ± 2 cps
Background Corrected Response *	314 ± 3 cps

* Mean background count-rate equivalent to $(149 \pm 2) \text{ s}^{-1}$.

† Uncertainties quoted are at the 1σ level.

Table 36 Example of Contiguous Portions Measurements

Source Orientation	Observed Detector Responses (cps) †
0°	151 ± 3 153 ± 3 156 ± 3
90°	154 ± 3 155 ± 3 152 ± 3
180°	151 ± 3 152 ± 3 150 ± 3
270°	150 ± 3 156 ± 3 153 ± 3
Mean Response	153 ± 1 cps
Background Corrected Response *	4 ± 3 cps

This data refers to measurements performed with a piece of the very large area source placed in position 1 of the grid. The data for measurements in the remaining positions is summarised in Figure 39.

* Mean background count-rate equivalent to $(149 \pm 2) \text{ s}^{-1}$.

† Uncertainties quoted are at the 1σ level. The apparently large uncertainty in the overall net response is due to the statistical combination of the separate uncertainties in the mean response and the background countrate.

APPENDIX I

Members of the Collaborative Team

Clive Dray	Formerly of Bicron - NE
Alan Edwards	Defence Radiological Standards Centre, AWE Aldermaston
Caroline Felgate	National Physical Laboratory
John Keightley	National Physical Laboratory
Angela Nightingale	Formerly of the Regional Radiation Physics and Protection Service, Queen Elizabeths Medical Centre, Birmingham
Denise Peach	Regional Radiation Physics and Protection Service, Queen Elizabeths Medical Centre, Birmingham
Tony Richards	Radiation Protection Service, University of Leeds
Clare Scott	National Physical Laboratory
Mike Woods	National Physical Laboratory

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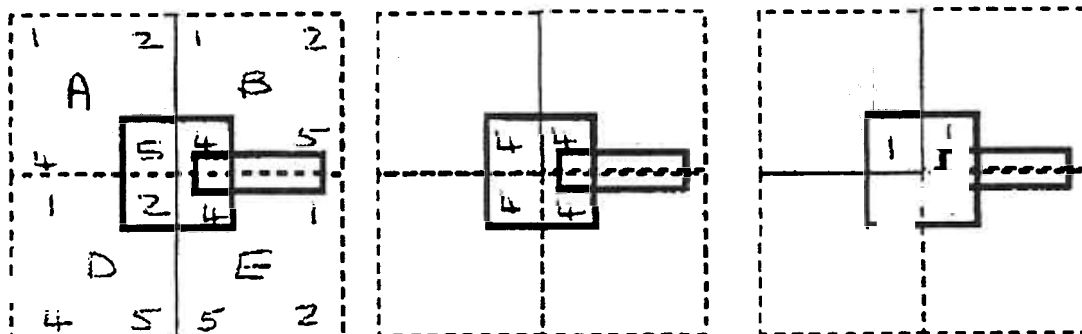
**NPL/DTI Provision of Guidance in the use of Relatively Small Sources for the Calibration
of Area Survey Instruments**

5. C-14 + BP7/4A probe

Normal

Best case

Worst case



Results

Operating voltage: 1230 v

Background: _____ cps

Normal

Source position on jig As indicated 'normal' above				
	A	B	D	E
	{5}	{4}	{2}	{4}
1				
2				
3				
4				
5				
Mean				
Mean - bkg				
				TOTAL A+B+D+E

Best case: Corner '4' of source under detector each time.

Background: _____ cps

Source position on jig As indicated 'best case' above				
	A	B	D	E
	{4}	{4}	{4}	{4}
1				
2				
3				
4				
5				
Mean				
Mean - bkg				
				TOTAL A+B+D+E

**NPL/DTI Provision of Guidance in the use of Relatively Small Sources for the Calibration
of Area Survey Instruments**

5. C-14 + BP7/4A probe continued

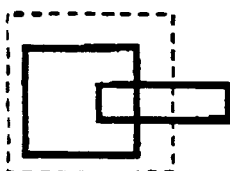
Worst case: Corner '1' of source under detector each time.

Background: _____ cps

Source position on jig As indicated 'worst case' above				
	A {1}	B {1}	D {1}	E {1}
1				
2				
3				
4				
5				
Mean				
Mean - bkg				
				TOTAL A+B+D+E

Probe in centre of source

Label each corner of source as used



	Inst reading
1	
2	
3	
4	
5	
Mean	

APPENDIX III

The Contiguous Portions Method : Recommended Protocol

Notes:

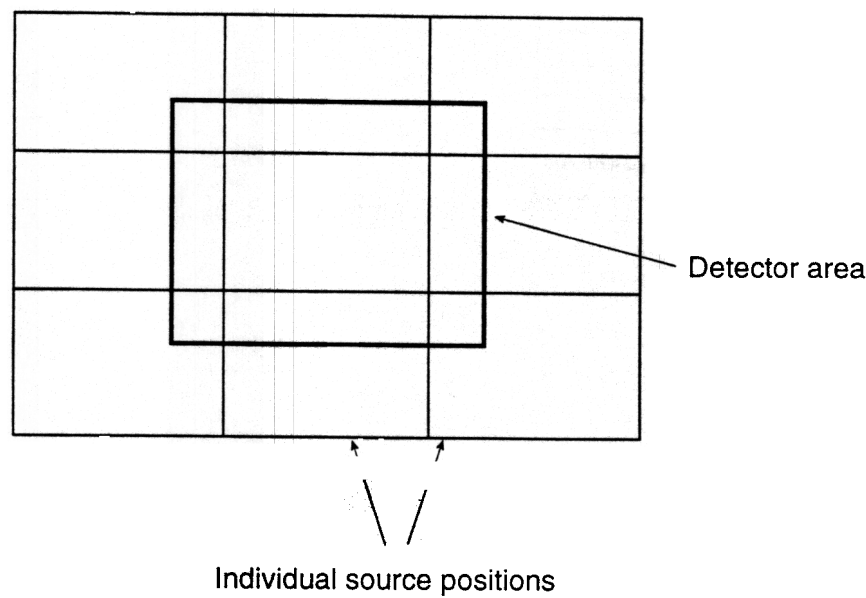
If performing the contiguous portions method for the first time using a particular detector, its' profile should be studied. Similarly for a calibration source which has not previously been used, the source uniformity must be determined. Details of these procedures are provided in the Annexe.

If a thorough detector profile has been performed, it is possible to make contiguous portions measurements to a percentage (perhaps 95 %), of the total detector response obtained during profiling. A correction factor can be applied to the results obtained from contiguous portions to account for the area not studied. An example of using a correction factor is also contained in the Annexe.

If the calibration source being used is rimmed, the source positioning grid should be drawn to accommodate this, ie, the active areas (rather than the outer edges of the source), should be adjacent and non-overlapping.

Preparation

Draw a grid of adjacent but not overlapping source positions (see Figure below), extending in all directions beyond the detector area to a chosen distance, determined from the detector profile



Fix the detector concentrically above the grid (with the centre of the detector coinciding with the centre of the central source position), so that the source - detector separation is 3 mm

Measurements

Record the background count-rate

Place the source in the first position on the grid, ensuring it lies within the lines

Measure the detector response

- Rotate the source through 90° and record the observed count-rate

Repeat the measurement for additional source rotations to 180° and 270°

Calculate the mean detector response for all four source orientations

Move the source to the next position on the grid, perform measurements in the four source orientations and calculate the mean value

Continue measurements until all positions on the grid have been studied

Record the background count-rate

Analysis

Calculate the mean of the background count-rates measured (B)

Subtract the mean background (B), from each of the mean count-rates observed (R_i) with the source in each of the positions on the grid

Calculate the sum of the background corrected detector responses, $\sum (R_i - B)$ and apply a correction factor if necessary

To obtain the detector efficiency as detailed in paragraph 103 of HS(G)49, divide the corrected total detector response, $\sum (R_i - B)$, by the product of the number of source positions (n), and the surface emission rate per unit area (SER), of the calibration source as detailed in the formula below

$$\text{Detector Efficiency} = \frac{\sum_{i=1}^n (R_i - B)}{n \cdot \text{SER}} \times 100 \%$$

where R_i is the detector response at source position i (cps)
 B is the background count-rate (cps)
 n is the number of source positions
 SER is the surface emission rate per unit area ($\text{s}^{-1} \cdot \text{cm}^{-2}$)

Annexe

Determination of a Detector Profile

Mount a suitable probe concentrically above a point source of the radionuclide to be studied, at a separation of 3mm from the filter if one is required, or from the active plane otherwise

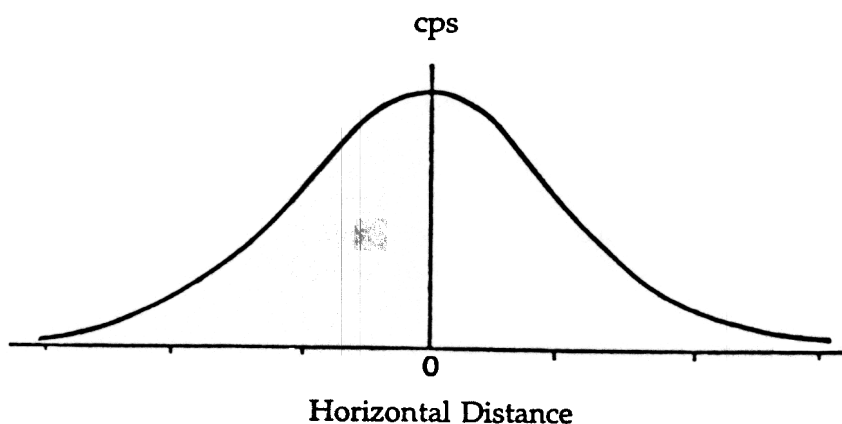
Fix a ruler or suitable scale to the bench top so that the origin coincides with the centre of the active area of the source

Remove the source from beneath the detector and measure the background count-rate

Replace the source at the origin and record the detector response to it

Measure the detector response at regular intervals (0.5 or 1 cm would be suitable) in both directions from the origin until the responses observed are consistent with the background count-rate

Plot the results to obtain a graph of a similar shape to that shown below (note for α -emitters the curve will have a flatter response about the origin and a steeper decline)



Calculate and plot the cumulative detector response (the running total of response observed against horizontal distance)

Determine the fraction of the total response for which contiguous portions measurements will be made; it is not necessary to perform measurements to the distance at which the detector response reaches background

Apply a correction factor to the total detector response from the contiguous portions measurements to take into account the percentage of detector response that was not studied

Determination of Source Homogeneity

Divide the surface of the large area source under study into equal portions of area not greater than 10 cm^2 (according to ISO 8769)

Determine the background count-rate using a monitor appropriate to the radionuclide under examination

- Using an attenuating mask of sufficient density and thickness to attenuate all radiations emitted from the source, expose the monitor to each of the individual portions in turn

Determine the mean value of the background corrected detector responses observed

Calculate the percentage by which each portion of the source deviates from the mean value

- Determine the standard deviation in the mean of the detector responses, to give the overall uniformity of the source

Use of Correction Factors

The grid area over which contiguous portions measurements are made can be reduced by adopting a horizontal measurement distance which is a known percentage of that determined during the detector profile. The summed detector response resulting from those contiguous portions measurements will then be that same percentage of the total response that would have been obtained if measurements had been made over the whole grid area. A correction factor can be applied to the results obtained from contiguous portions to account for the area not studied.

If a cumulative detector response like that shown below were obtained for a particular probe - source combination, a grid area of 400 cm^2 would be necessary to study the whole of the detector response. However, an area of 49 cm^2 (corresponding to a horizontal distance of 7 cm and 95 % of the cumulative detector response) could be reasonably studied and a

multiplication correction factor of 1.05 applied to the summed detector response, substantially reducing the measurements required.

