



**AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS**

**THE AUDIT OF RADIOACTIVE EFFLUENT RELEASED
INTO THE WORONORA RIVER, NSW**

by

S.R. ISAACS

April 1979

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ABSTRACT

The radioactive effluent released from the AAEC Research Establishment at Lucas Heights into the estuary of the Woronora River, NSW, has been audited internally since 1961. This report describes the duties of the Effluent Audit Officer and the apparatus and analytical methods used.

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1. INTRODUCTION

Since June 1961, an Effluent Audit Officer has been responsible for independent analysis of radioactivity in the effluent released into the Woronora River from the AAEC Research Establishment (AAECRE) at Lucas Heights. This report, which provides for the possibility that the task could be taken over by an external authority, describes the duties of and analytical techniques used by the Effluent Audit Officer.

2. THE DISCHARGE AUTHORISATION

The discharge formula for Research Establishment effluent was first authorised in early 1961 by the Maritime Services Board of New South Wales and the New South Wales Radiological Advisory Council [Wilson 1959]; this formula was as follows:

$$650 \text{ Ra} + 52 \text{ (other } \alpha\text{-emitters)} + 33 \text{ (Ca+Sr)} + \\ + \text{all other } \beta\text{-emitters} \leq \frac{V}{3 \times 10^6} \text{ Ci/month,}$$

where Ra = the radium-226 content (Ci),
(other α -emitters) = the remaining α -activity (Ci),
(Ca+Sr) = the combined radiocalcium and radiostrontium (Ci),
all other β -emitters = the remaining β -activity (Ci), and
V = the volume (gallons) discharged during the month, or
 3×10^6 gallons, whichever is the smaller.

In 1966, after a reconsideration of the levels of permissible discharge, a new formula was introduced [Fry 1966] which took into account three main pathways that could lead to the exposure of the general public to the radioactivity released into the Woronora Estuary. They were:

- (i) The ingestion of sea food, especially oysters.
- (ii) The incorporation into the body (for example in cuts) of sand contaminated with α -emitters.
- (iii) Sunbathing on β -contaminated sand.

On these bases, Fry determined the maximum permissible monthly discharge limits (mpmd) which are still used to calculate the discharge authorisation (Table 1), which is expressed in the form

$$\sum_i \frac{X_i}{(\text{mpmd})_i} \leq \frac{V}{3 \times 10^6} ,$$

where X_i = the amount of the i^{th} nuclide discharged in a month
(MBq)

(mpmd) $_i$ = the maximum permissible monthly discharge of the i^{th}
nuclide (MBq), and

V = the number of gallons of effluent discharged in a
month or 3×10^6 gallons, whichever is the smaller.

(Fry's original figures have been converted to SI units using the relationship $1 \text{ Ci} = 37 \text{ GBq}$. For convenience the term $\frac{V}{3 \times 10^6}$ is retained and calculated in gallons.)

At first sight, the formula seems too demanding for effluent operation but, because of the low level of activity in the effluent, the analytical discrimination of nuclides is not usually required and only gross α - and β -activities and γ -spectrometry are necessary. For example, the most restrictive α -emitter is ^{210}Po ; if the total activity discharged remains below the mpmd for this nuclide ($3.7 \times 10^2 \text{ MBq}$), then no specific determination for individual α -emitters is required. When the total α -activity rises above this level, it then becomes necessary to analyse for ^{210}Po [Flynn 1968] to demonstrate its absence or that it is present in insignificant quantities. The restriction upon the unidentified total α -activity is controlled by the next most hazardous radio-nuclide, ^{226}Ra , which has an mpmd of 1.07 GBq .

Only low level waste is discharged from the Research Establishment; this is approximately 1/10th of the maximum permissible discharge. Clearly, the discharge of higher levels of waste would require closer control and analytical discrimination between nuclides as is applied in nuclear power stations [Dutton & Harvey 1967]. Table 2 summarises the total audited amount of radioactivity discharged from the Research Establishment between the years 1961-1977.

3. THE DUTIES OF THE AAECRE EFFLUENT AUDIT OFFICER

During the past ten years, the duties of the AAECRE Effluent Audit Officer have been modified to suit the reformulation of the Lucas Heights liquid effluent discharge authorisation; these now include auditing the Effluent Control Group records on the release of radioactivity. Audit of these records is supplemented by independent spot checks on samples taken from the pipeline to the Woronora River and monthly 'composites' are prepared from all pipeline samples. Spot samples and monthly composites are analysed for gross α - and gross β - activity. Tritium and

γ -spectrometry analyses are also performed on monthly composites to ascertain that the total radioactivity released satisfies the limitations of the discharge authorisation.

Occasionally, γ -spectrometry is performed on samples taken from holding tanks that contain unusually high gross β -activities for the identification of $\beta\gamma$ nuclides. Radiochemical separations are sometimes carried out on pipeline samples to aid in the interpretation of γ -spectrometry data.

4. THE MEASUREMENT OF RADIOACTIVITY

Although there are numerous publications that provide methods for the analysis of radioactivity, the apparatus and techniques employed by the Effluent Audit Officer are described to serve as a guide for an external auditor.

4.1 Apparatus

Counting of α - and β -activity

An internal gas flow proportional counter was selected for counting gross α - and β -activity because of its superiority over other detection methods. It is highly sensitive over a wide range of β energies and highly efficient owing to the good geometry (2π) produced by the introduction of the sample into the counting chamber.

The Nuclear Chicago spectro-shield low background counting system is used in the windowless mode for gas proportional counting of low α - and β -activities. This system consists of four major components (Figure 1):

- (a) A guarded detector assembly comprising a meson-guarded gas flow detector assembly and a radiation shielding device.
- (b) A shield support structure.
- (c) A Nuclear Chicago model 1105 analyser/controller consisting of analyser and sample changer control circuits.
- (d) A sample changer mechanism.

The scintillation guard detector effectively cancels the heavily ionising, high energy component of the environmental background radiation, and the lead/copper shielding minimises the X- and γ -ray components.

Output signals are collected on a Nuclear Chicago type 8703 scaler connected to a Model 8437 printout device.

Counting of tritium

Tritium is counted on a Beckman type LS11 liquid scintillation system. It has two basic units - an automatic three channel instrument and a modified model 33 teletypewriter. Six standard ISO-SET plug-in modules and a trimmable ISO-SET are also available for the analysis of one nuclide in the presence of another.

γ -spectrometry

Gamma-spectrometry is performed on a whole body monitor using a 20 x 10 cm NaI(Tl) Harshaw type 32 MBS 16/B crystal with low potassium content. The crystal is viewed by three 7.5 cm de-based phototubes which are linked to a computer analysis system developed by the AAEC.

5. COUNTING PROCEDURES

5.1 α -counting

A 20 mℓ sample of effluent is evaporated on an aluminium planchet (5 cm diameter) placed on top of a water bath. The planchet is previously washed with acetone to remove grease. The effluent sample is transferred from a beaker on to the planchet in 2-3 mℓ portions using a Pasteur pipette. When the sample is completely evaporated, the planchet is transferred to a desiccator for 10 minutes before counting. A clean planchet is also counted for a background measurement and another planchet containing a standard ^{241}Am source is included to provide an efficiency check which varies from 43-45 per cent. It is assumed that the gross unidentified α -activity of the sample is counted with the same efficiency.

Before the instrument is used, a plateau check of count rate vs voltage is obtained with the ^{241}Am source (see Figure 2); this provides the optimum working voltage. A χ^2 test on the counter is also carried out (see Appendix A). Figure 3 demonstrates the characteristics of the plateaus obtained from evaporated solutions of thorium, uranium and polonium-210 which were produced as 'extended' sources over an area of approximately 20 cm²; these were prepared in the same way as the samples analysed for gross α -activity. The optimum voltage for the extended source is closer to the end of the plateau which is not as well defined as that of the point source.

The normal counting time for both the sample and background is 100 min. Since the counter background is approximately 0.1 count min⁻¹, the minimum detectable limit of α -activity can be calculated from the

formula [Palmer 1958]:

$$C_m = \sqrt{8bg/t}$$

where C_m = minimum detectable count rate,
 bg = background count rate (counts min^{-1}), and
 t = time of counting (min).

With counting efficiency of 45 per cent, a minimum detectable limit for a 20 ml sample is $0.2 \times 10^{-3} \text{ Bq ml}^{-1}$.

The predominant dissolved solid in the effluent is sodium sulphate which averages 200 mg l^{-1} . This results in a sample thickness of 0.2 mg cm^{-2} on a planchet. Although there is a reduction of counting efficiency (absorption factor ~ 0.9) for a sample thickness of 0.2 mg cm^{-2} , this can be neglected as it is less than counting statistics.

It has been suggested that ^{210}Po is volatile at higher temperature, so the possibility of losses by volatilisation of ^{210}Po in effluent samples during evaporation under an infrared lamp placed approximately 20 cm from the planchet was investigated. Five 5 ml aliquots of a ^{210}Po solution were evaporated under an infrared lamp and another five samples were evaporated on a water bath. There was no difference in the average count rate, which confirmed that a water bath can be replaced with an infrared lamp for the evaporation of effluent samples, assuming that there are no other nuclides of low volatility.

5.2 β -counting

The planchets containing evaporated effluent samples and used for α -counting are also used for β -counting, in which case the voltage setting on the spectro-shield is higher. It should be noted that α -emitters contribute to gross β -count rates at higher voltages but, as the gross α -activity in effluent is generally less than 10 per cent of the β -activity, this contribution is minimal and can be ignored. However, if the concentration of α -activity in effluent is high, allowances must be made for its contribution to gross β -activity.

A large number of β -emitting nuclides can be present in radioactive effluent. Table 3 lists the more important nuclides together with the efficiency of the Nuclear Chicago gas proportional counter. A ^{90}Sr standard is used to calibrate the instrument which, for this nuclide, has an efficiency of 50-53 per cent. Figure 4 gives the differences in plateau characteristics between a 'point' and an 'extended' ^{90}Sr source. It is assumed that the gross unidentified β -activity is counted with the

same efficiency as ^{90}Sr . Figures 5 and 6 further illustrate the differences in plateaus between point and extended sources for ^{60}Co and ^{137}Cs .

When it is necessary to discriminate between nuclides, corrections are made for the intrinsic efficiency of each nuclide contributing to the gross β -activity. Thus, if ^{65}Zn has been detected in the γ -spectrum of an effluent sample, solvent extraction and γ -spectrometry are used for more accurate determination, should the ^{65}Zn peak be masked by an appreciable quantity of ^{60}Co [Isaacs 1970]. It is to be noted that the efficiency for counting ^{65}Zn is 16 per cent (Table 3), hence the gross β -activity is reduced accordingly. Generally, total activity levels are sufficiently low not to warrant such discrimination.

The counting time for β -activity is 60 min. The background count rate is 3 counts min^{-1} and, with a counting efficiency of 50 per cent, a minimum detectable limit of $0.1 \times 10^{-2} \text{ Bq mL}^{-1}$ is obtained for a 20 mL sample (see Section 5.1).

Figure 7 shows the effect of sample thickness on some nuclides counted in the Nuclear Chicago instrument.

5.3 Tritium Counting

A sample of effluent is distilled and 3 mL of the distillate is pipetted into a liquid scintillation counting vial. To this is added 15 mL of a scintillant containing 100 g of naphthalene and 4 g of 2,5-diphenyloxazole (PPO) dissolved in 1 L of redistilled dioxan. Three millilitres of a standard solution of tritiated water and 3 mL of distilled water are similarly treated. The cocktail mixtures are shaken for a minute until homogeneous and stored overnight in a dark cupboard. Counting is performed the next day with minimum exposure to light to avoid chemiluminescence. The background count rate is approximately 36 counts per minute. The minimum detectable tritium activity is 0.1 Bq mL^{-1} for a 20 minute count. With a gain of 360, the efficiency of the instrument for tritium is approximately 18 per cent.

5.4 γ -spectrometry

Two litres of an effluent sample is evaporated in a dish lined with aluminium foil. The foil is then folded to approximately 9 cm diameter for counting on the face of a 20 x 10 cm NaI(Tl) crystal of the whole body monitor. Photopeak counting efficiencies for γ -energies in the range 0.32-1.46 MeV have been determined for the Petri dish geometry [Finn 1964]. Samples are usually counted for 100 min. The folded foils

vary in shape, but the actual counting geometry is somewhere between that for a Petri dish and that for a point source at 2 mm from the stainless steel jacket of the detector. For a point source, the counting efficiency is some 12 and 18 per cent higher than the Petri dish geometry at 0.32 and 1.46 MeV respectively.

No correction is made for absorption. When ^{60}Co is evaluated, a correction is made to the photopeak counts to allow for losses resulting from the summing of cascade gammas. The probability of this occurring is relatively high owing to the near 2π geometry of the system.

Short-lived radionuclides are rarely identified in the effluent, the shortest being ^{131}I ($t_{1/2}$ 8 days).

6. CALCULATION OF ACTIVITY

Five 100 min counts are usually taken for α -activity determinations and three 60 min counts for β -activity, giving a standard deviation of ± 18 per cent and ± 3 per cent respectively for the average effluent sample.

The α - and β -activities of a sample are calculated from the following relationship:

$$\text{Activity kBq ml}^{-1} = \frac{37}{2.22 \times 10^6} \times \frac{C}{V} \times \frac{1}{S} \times \frac{1}{E},$$

where C = count rate in counts min^{-1} corrected for background,
 V = sample volume in ml (usually 20 ml),
 S = source self-absorption factor (assumed to be 1), and
 E = counter efficiency.

Tritium activity is calculated similarly but with the exclusion of the source self-absorption factor.

When a separate determination for an individual β -nuclide is performed, a correction is made for self-absorption when determining its final contribution to the gross activity using the data available from Figure 8.

Table 4 summarises the characteristics of the counters used for analysis.

7. ACKNOWLEDGEMENT

The aid of Mr D.E. Parsons in the use of the whole body monitor for γ -spectrometry analysis of effluent samples is gratefully acknowledged.

8. REFERENCES

- Dutton, J.W.R. & Harvey, B.R. [1967] - Studies of liquid radioactive effluent discharged to the aquatic environment from CEGB nuclear power stations. A sequential scheme for the analysis of major metallic radioisotopes. *Water Res.*, 1 : 743-757.
- Finn, R.J. [1964] - Photopeak efficiencies for NaI(Tl) crystals for point and extended sources. AAEC/TM268.
- Flynn, W.W. [1968] - The determination of low levels of polonium-210 in environmental materials. *Anal. Chim. Acta*, 43 : 221-227.
- Fry, R.M. [1966] - A reformulation of the Lucas Heights liquid effluent discharge authorisation. AAEC/E156.
- Isaacs, S.R. [1970] - Determination of zinc-65 in Lucas Heights effluent. AAEC/TM569.
- Palmer, A.R. [1958] - The determination of radioactivity in AAEC effluent. Part 1 - Determination of total alpha emitters. AAEC unpublished report.
- Wilson, A.R.W. [1959] - Safe levels for the discharge of radioactive effluent into the Woronora Estuary. AAEC unpublished report.

TABLE 1
 NUCLIDES LISTED IN ORDER OF THEIR MAXIMUM PERMISSIBLE MONTHLY
 DISCHARGES CONSIDERING BOTH INTERNAL AND EXTERNAL RADIATION EXPOSURE
 PATHWAYS AND LIMITED TO A MAXIMUM OF 3.7×10^4 GBq FOR TRITIUM
 AND 3.7×10^3 GBq FOR ALL OTHER NUCLIDES
 [AFTER FRY 1966]

mpmd	Nuclide			
< 3.7 GBq	^{210}Po (0.37) ^{228}Ra (3.18)	^{226}Ra (1.07) ^{65}Zn (3.52)	$^{114}/^{114\text{m}}\text{In}$ (1.07)	^{32}P (2.11)
3.7-37 GBq	^{115}In (4.8) ^{52}Mn (10.4) $^{230}\text{Th}, ^{232}\text{Th}$ (10.7) ^{181}W (21.1) $^{238}\text{Pu}, ^{239}\text{Pu}, ^{242}\text{Pu}$ (26.6)	^{231}Pa (4.8) ^{96}Tc (10.7) ^{187}W (11.8) $^{241}\text{Am}, ^{243}\text{Am}$ (21.1) ^{243}Cm (26.6)	^{185}W (5.2) ^{210}Pb (10.7) ^{237}Np (15.9) $^{245}\text{Cm}, ^{246}\text{Cm}$ (21.1) ^{59}Fe (29.6)	Th nat (5.2) ^{227}Ac (10.7) ^{129}I (21.1) ^{249}Cf (21.1) ^{99}Tc (31.8)
37-370 GBq	^{228}Th (37) $^{97\text{m}}\text{Tc}$ (40.7) ^{106}Ru (51.8) $^{223}\text{Ra}, ^{224}\text{Ra}$ (55.5) ^{140}Ba (66.6) ^{166}Ho (74) ^{140}La (92.5) $^{126}\text{I}, ^{131}\text{I}$ (107.3) ^{143}Ce (114.7) ^{47}Ca (140.6) ^{48}Sc (159.1) ^{36}Cl (185.0) ^{97}Tc (210.9) ^{182}Ta (210.9) ^{63}Ni (318.2)	^{244}Cm (37) ^{90}Sr (44.4) $^{115}/^{115\text{m}}\text{Cd}$ (51.8) ^{241}Pu (51.8) ^{141}Ce (66.6) ^{60}Co (77.7) ^{137}Cs (103.6) ^{154}Eu (107.3) ^{147}Nd (125.8) ^{143}Pr (151.7) ^{48}V (159.1) ^{58}Co (188.7) $^{127}/^{127\text{m}}\text{Te}$ (210.9) ^{192}Ir (210.9) ^{95}Zr (318.2)	^{252}Cf (37) ^{90}Y (44.4) $^{202}\text{Tl}, ^{204}\text{Tl}$ (51.8) "Other α " (55.5) ^{89}Sr (74) $^{129}/^{129\text{m}}\text{Te}$ (77.7) ^{76}As (107.3) ^{203}Hg (107.3) ^{111}Ag (129.5) ^{170}Tm (151.7) $^{110\text{m}}\text{Ag}$ (159.1) ^{46}Sc (210.9) ^{160}Tb (210.9) ^{200}Tl (210.9)	^{54}Mn (40.7) ^{144}Ce (48.1) ^{250}Cf (51.8) ^{86}Rb (59.2) ^{91}Y (74) ^{122}Sb (85.1) ^{109}Cd (107.3) ^{234}Th (107.3) ^{149}Pm (129.5) ^{193}Os (151.7) ^{201}Tl (177.6) ^{74}As (210.9) ^{166}Dy (210.9) ^{22}Na (307.1)
370-3700 GBq	^{181}Hf (370) ^{103}Ru (407) ^{113}Sn (481) ^{177}Lu (481) ^{191}Pt (518) ^{136}Cs (703) ^{124}Sb (1073) ^{191}Os (1073) ^{14}C (1406) ^{59}Ni (3249) ^{95}Nb (4104) ^{183}Re (4902)	^{185}Os (370) ^{153}Sm (407) ^{169}Er (481) ^{51}Cr (518) ^{233}Pa (518) ^{198}Au (888) ^{147}Pm (1073) ^{197}Hg (1073) ^{103}Pd (1591) ^{97}Ru (2109) ^{73}As (2664) $^{196}\text{Au}, ^{199}\text{Au}$ (3515)	^{77}As (407) ^{152}Eu (407) ^{186}Re (481) ^{105}Rh (518) ^{239}Np (518) ^{134}Cs (962) ^{155}Eu (1073) ^{230}Pa (1073) ^{132}Te (1591) ^{131}Ba (2109) ^{171}Tm (2664)	^{82}Br (407) ^{47}Sc (481) ^{175}Yb (481) ^{105}Ag (518) ^{55}Fe (703) ^{99}Mo (1073) ^{153}Gd (1073) ^{57}Co (1147) ^{197}Hg (1591) ^{151}Sm (2109) $^{131\text{m}}\text{Te}$ (3182)
3.7×10^3 GBq	^7Be ^{35}S ^{45}Ca ^{75}Se ^{71}Ge ^{85}Sr ^{87}Rb $^{93\text{m}}\text{Nb}$ ^{93}Zr ^{125}Sb $^{125\text{m}}\text{Te}$ ^{131}Cs ^{135}Cs ^{187}Re ^{193}Pt $^{193\text{m}}\text{Pt}$ ^{203}Pb ^{206}Bi ^{207}Bi ^{210}Bi			
3.7×10^4 GBq	^3H			

TABLE 2
SUMMARY OF EFFLUENT DISCHARGES 1961-1977

Year	Vol Dis- charged $\times 10^3 \text{ m}^3$	Gross α MBq	Gross β MBq	^3H GBq	^7Be MBq	^{60}Co MBq	^{106}Ru MBq	$^{95}\text{Zr-Nb}$ MBq	^{134}Cs MBq	^{137}Cs MBq	^{144}Ce MBq	^{51}Cr MBq	^{131}I MBq	^{65}Zn MBq	^{54}Mn MBq	^{169}Yb MBq	$^{114/114\text{m}}$ In MBq	^{226}Ra MBq	^{90}Sr MBq
1961 (Total 9 months)	55	40.7	2183	-		196				466								4	655
1962	74	37.0	1739	925		59				603								4	181
1963	65	50.8	3774	1739		234		144	41	1883								4	636
1964	81	14.8	2516	1036		70		200		659								4	381
1965	85	59.2	2294	3774	148	252		155	41	255								8	155.4
1966	92	74.0	518	1729	429.2	940	178	218		215		444							
1967	93	70.3	2183	2257		407	22	118	104	784	44		7						
1968	95	55.5	2257	2183		1232			44	522	37		15						
1969	100	99.9	1739	1554		1358		70	30	392		33	44	30			7+		
1970	86	140.6	2738	6068		744		33		315	26	514	100	107			7+		
1971	95	107.3	2257	4427		747			19	340			15	41					
1972	101	144.3	2923	4329		1010		7		640		141		37	26		7+		
1973	99	33.3	3330	1295		740				529		141	4		100	33	7+		
1974	101	33.3	1739	888		259		11		252					63	48	15		
1975	94	29.6	1110	1184		207			41	163			15	63	7		89*		
1976	105	44.4	1406	1406		229				163		259			4		89*		
1977	106	25.9	1850	777		196			22	107		89	22	118			89*		

* Minimum detectable level by γ -spectrometry

+ $^{114/114\text{m}}$ Indium determination on a monthly composite only.

TABLE 3
EFFICIENCIES OF NUCLIDES THAT CONTRIBUTE
TO GROSS β -ACTIVITY

Nuclide	Mode of Disintegration	Efficiency (%)
^{137}Cs	β - γ	55
^{60}Co	β - γ	44
^{51}Cr	* E.C.; γ	22
$^{114\text{m}}\text{-}^{114}\text{In}$	γ, β^-, β^+	93
^{54}Mn	* E.C.; γ	28
^{65}Zn	$\beta^+; \gamma$	16
^{90}Sr	β - γ	53
^{59}Fe	β - γ	16

* Orbital Electron Capture

TABLE 4
CHARACTERISTICS OF COUNTERS

Counter Type	Background cpm	Efficiency (%)	Minimum Detectable Limit (Bq ml ⁻¹)
Nuclear Chicago α -counting	0.1	43-45	0.2×10^{-3}
Nuclear Chicago β -counting	3.0	50-53	0.1×10^{-2}
Beckmann Liquid Scintillation (^3H)	36	18	0.1

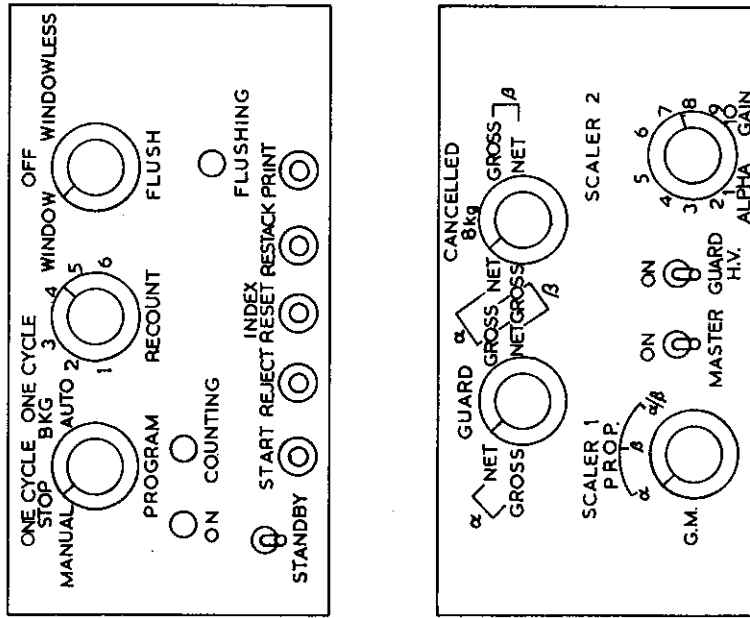
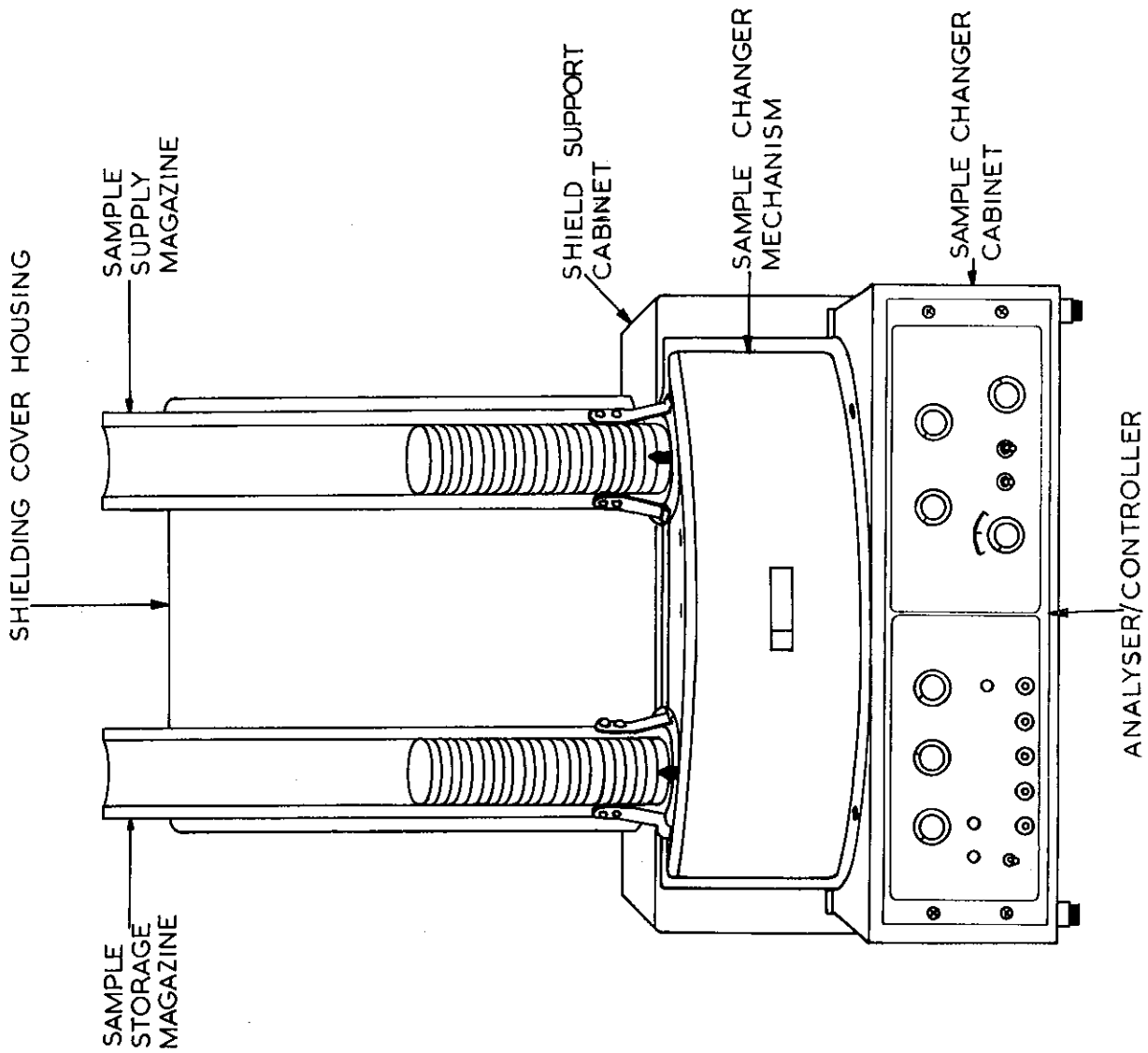


FIGURE 1. THE NUCLEAR CHICAGO SPECTRO-SHIELD LOW BACKGROUND COUNTING SYSTEM

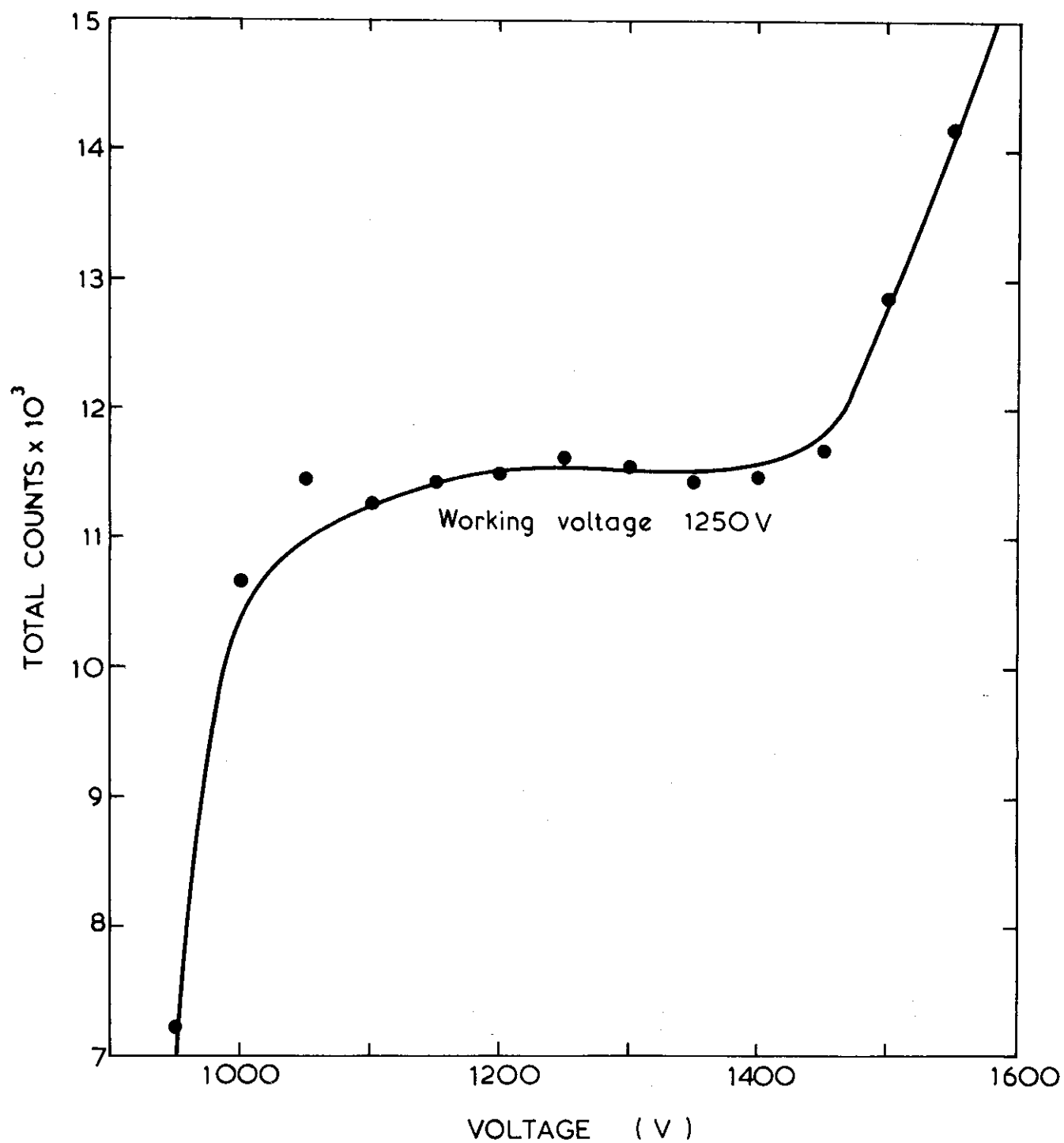


FIGURE 2. PLATEAU OF A STANDARD ²⁴¹Am POINT SOURCE

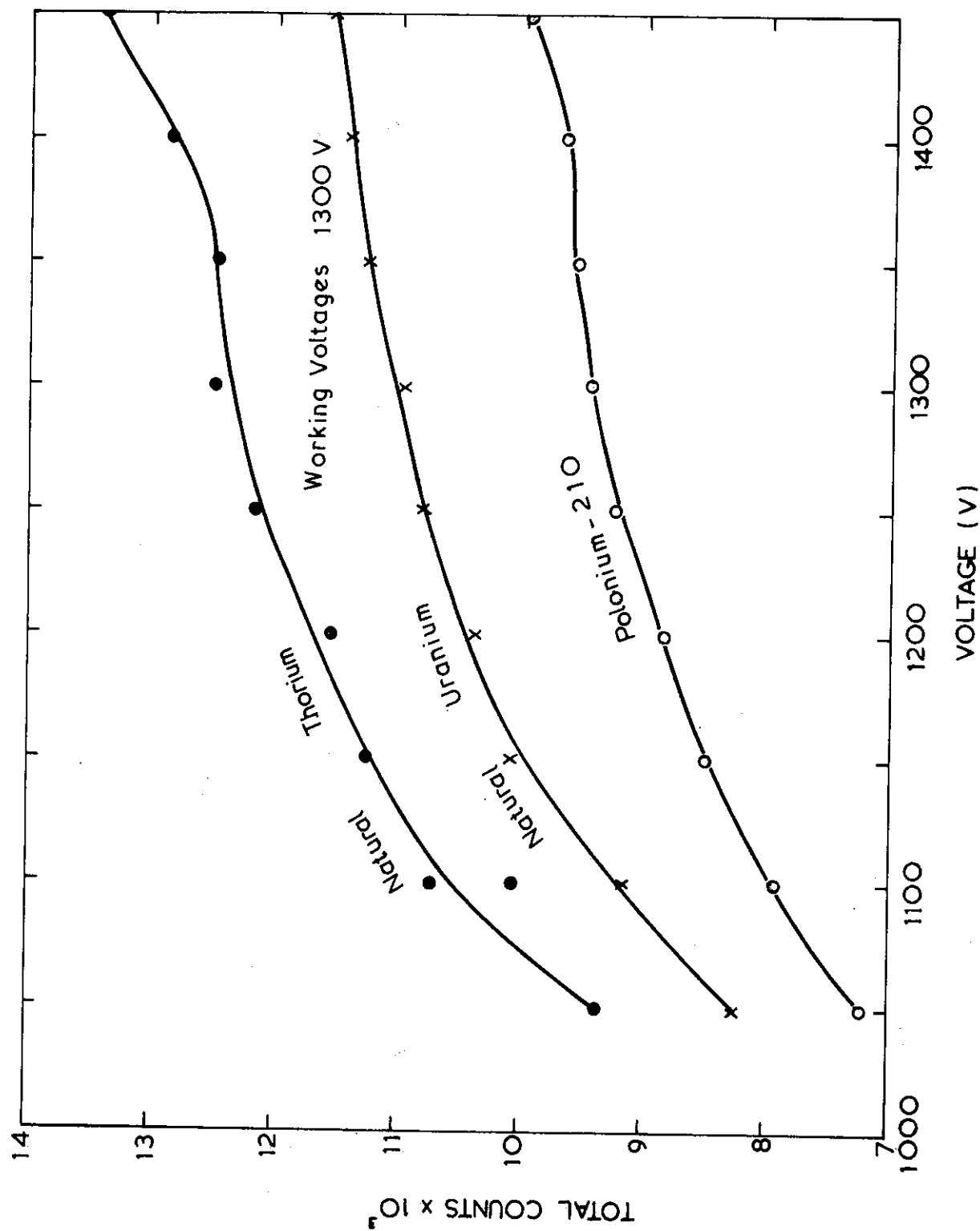


FIGURE 3. PLATEAU CHARACTERISTICS OF EXTENDED SOURCES

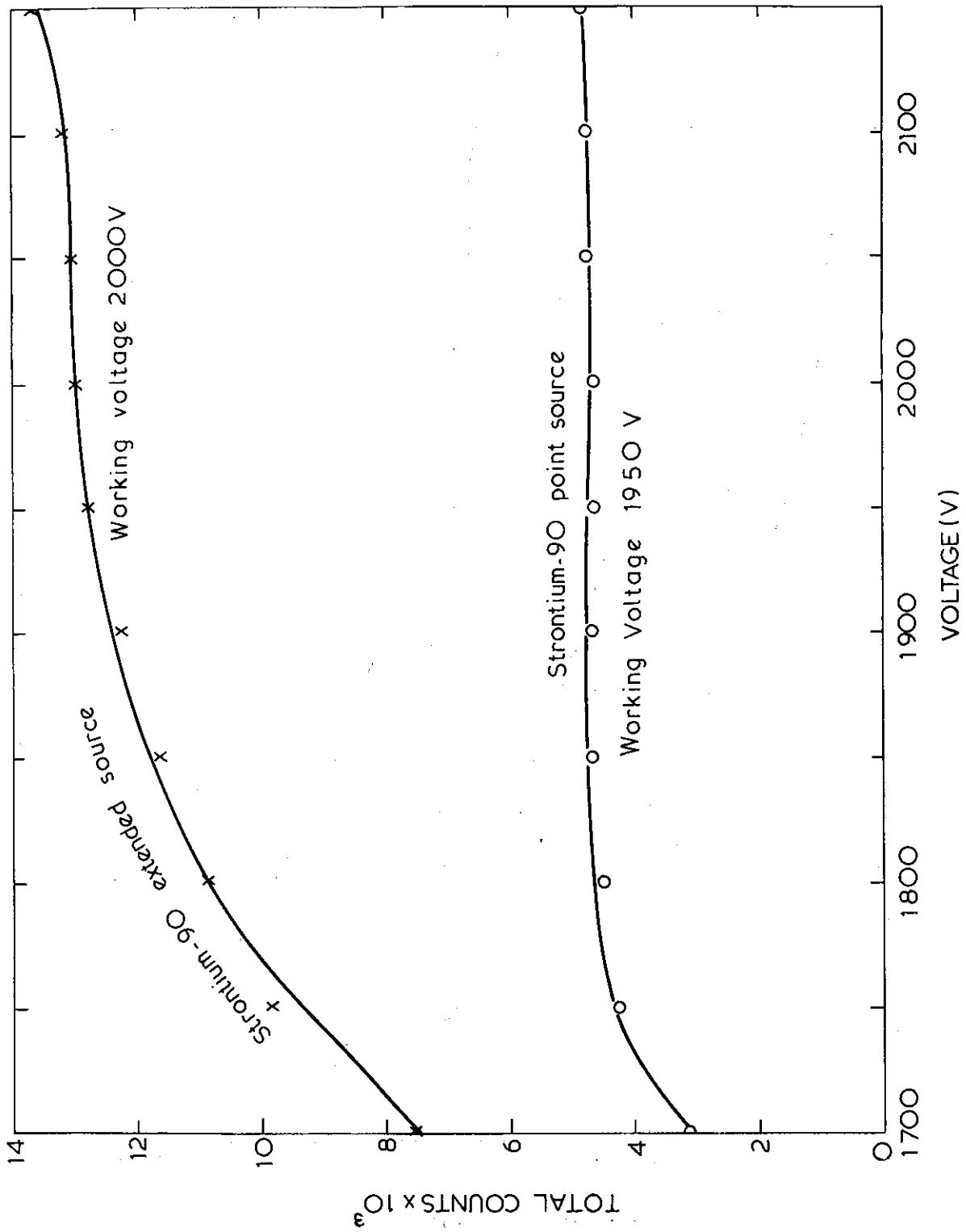


FIGURE 4. PLATEAU CHARACTERISTICS OF POINT AND EXTENDED SOURCES OF ^{90}Sr

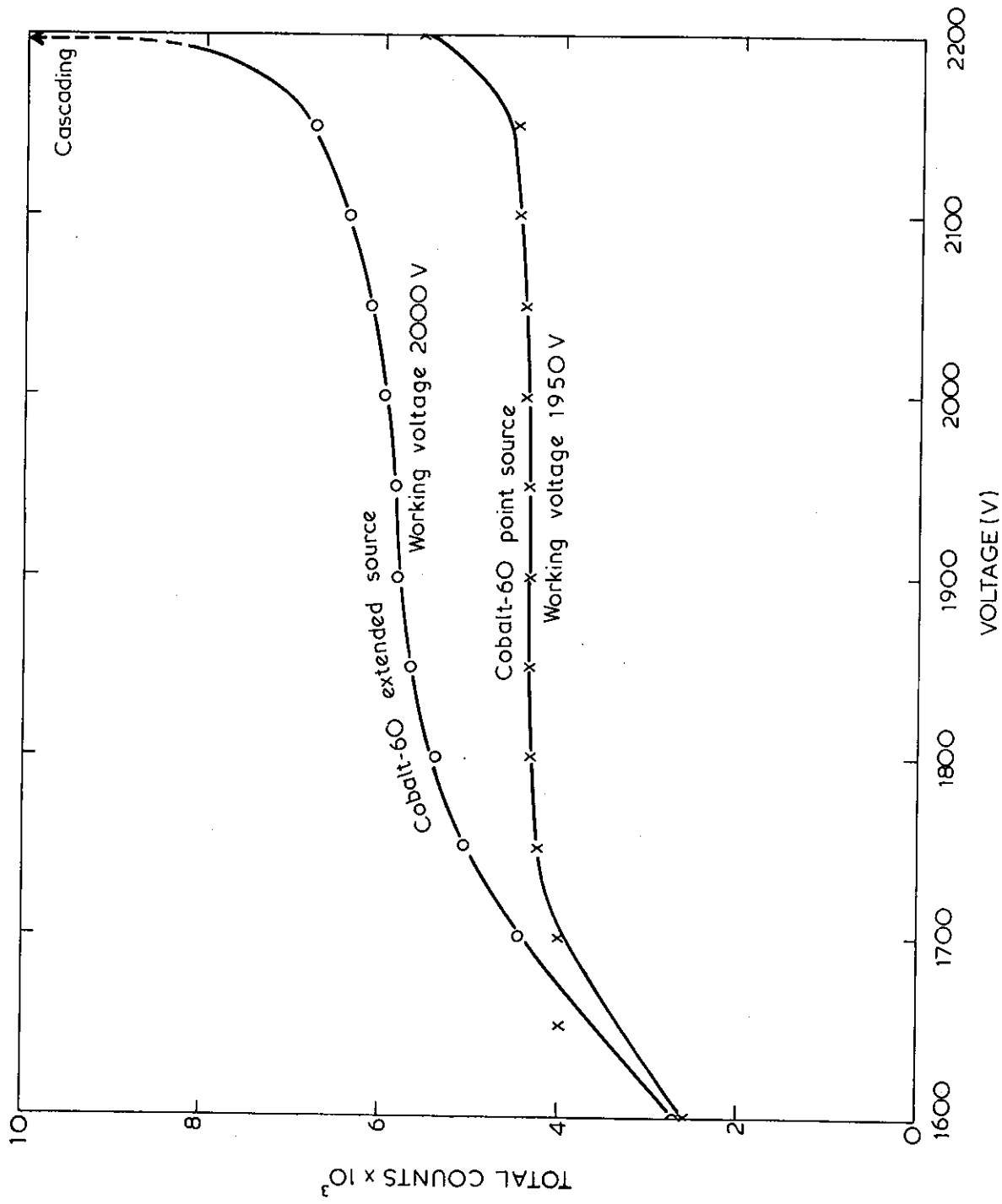


FIGURE 5. PLATEAU CHARACTERISTICS OF POINT AND EXTENDED SOURCES OF ^{60}Co .

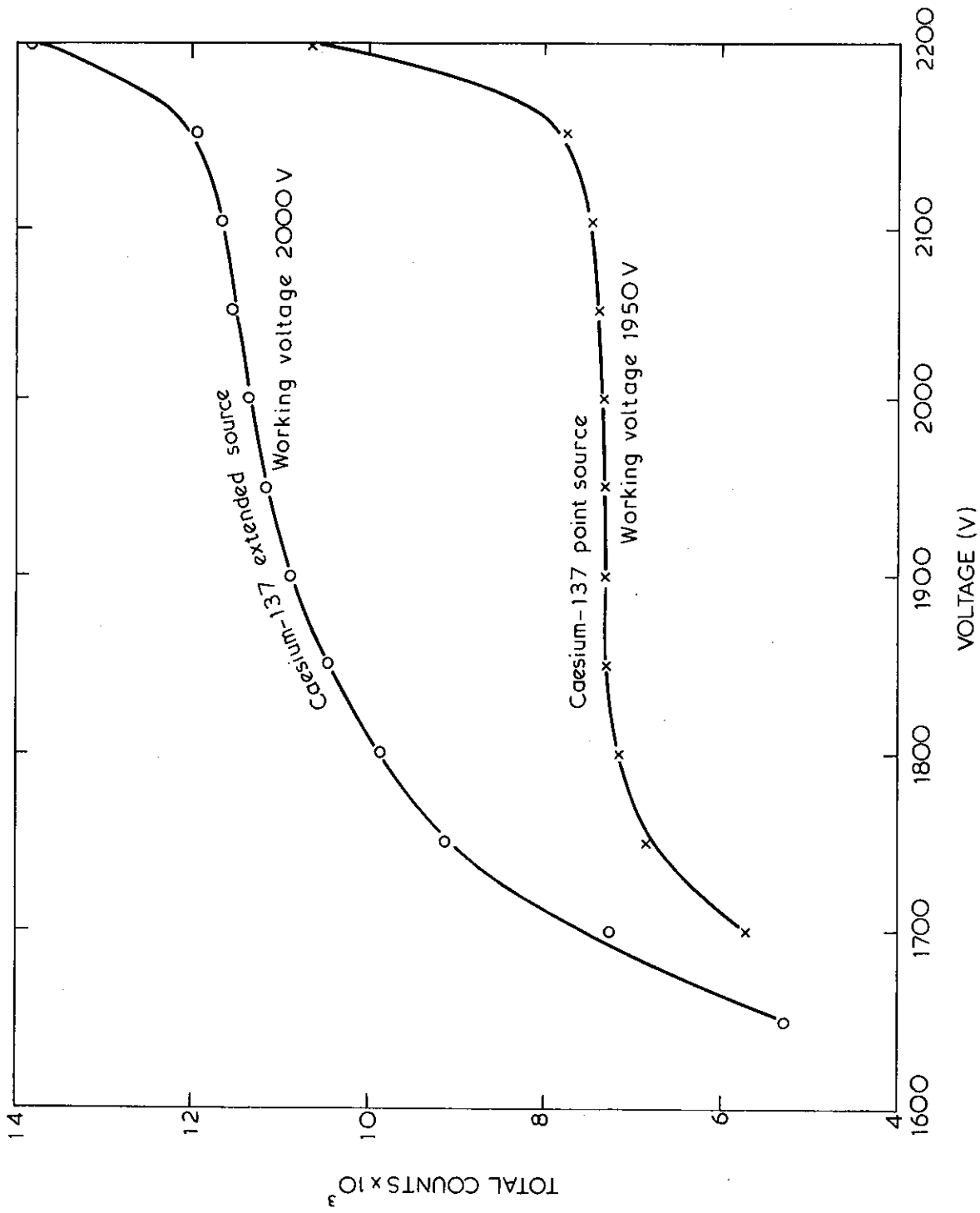


FIGURE 6. PLATEAU CHARACTERISTICS OF POINT AND EXTENDED SOURCES OF ¹³⁷Cs

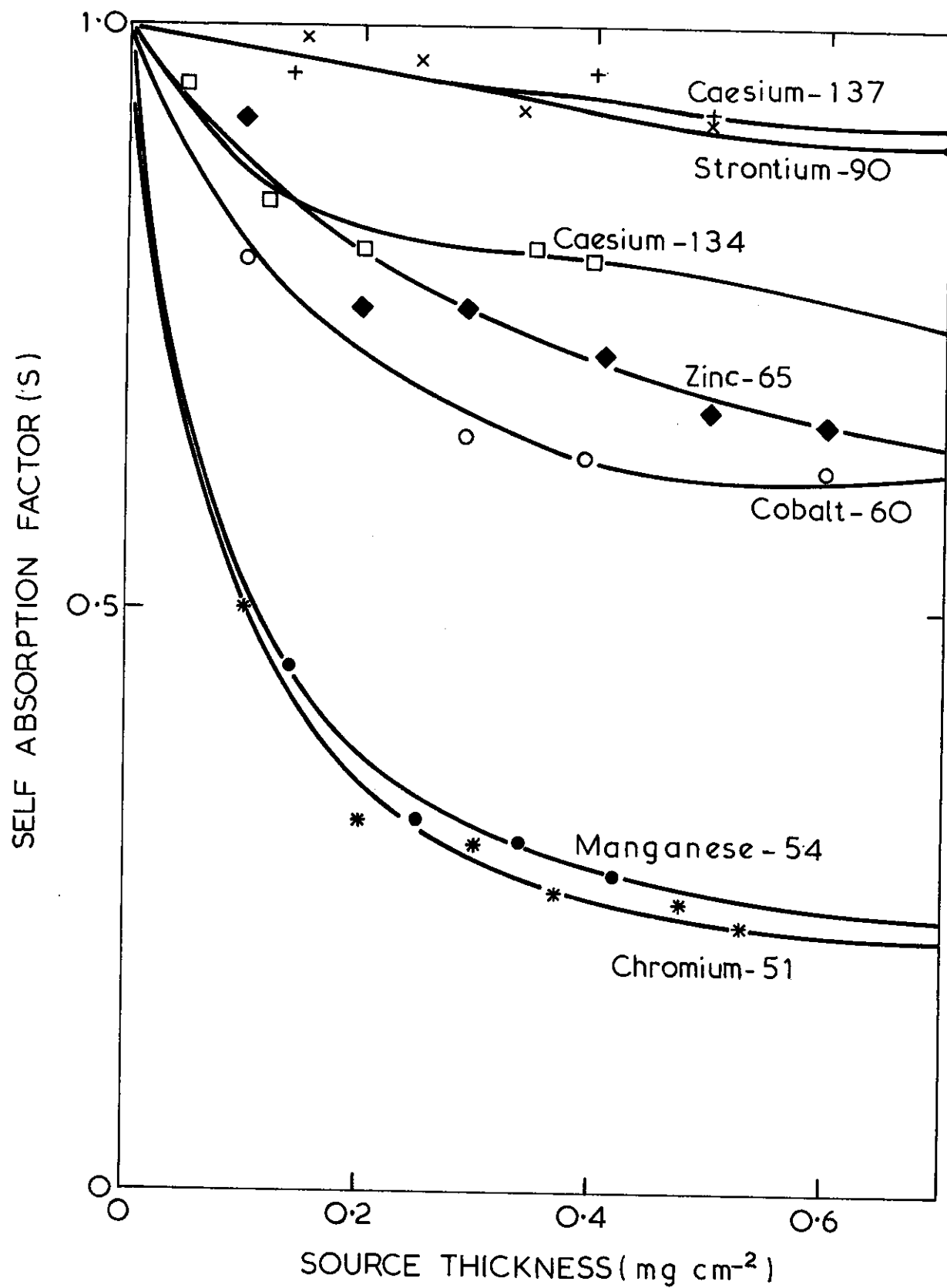


FIGURE 7. SELF ABSORPTION FACTOR FOR β CONTRIBUTING NUCLIDES AS A FUNCTION OF SOURCE THICKNESS

APPENDIX A
THE STATISTICAL ACCURACY OF COUNTING

A1. CALCULATION OF STANDARD DEVIATION

The precision of measured values is an expression of the magnitude of the spread of the individual observations about their average value.

A numerical evaluation of the precision of a set of measurements is given by the 'variance' σ_x^2 , where

$$\sigma^2 = \sum_1^N (x_i - \bar{x})^2 / N-1 ,$$

or by the standard deviation

$$\sigma = \sqrt{\sum_1^N (x_i - \bar{x})^2 / N-1} ,$$

where \bar{x} = average count rate,

x_i = the individual count rate, and

N = the number of individual observations.

For only a few determinations, such as three or four, N is used instead of $N-1$ as the divisor in the standard deviation expression.

The standard deviation is a more commonly used measure of deviation than the average deviation

$$\left(\sum_1^N \frac{x_i - \bar{x}}{N} \right)$$

because its value can be more reliably estimated from a given number of determinations in any statistical study.

A2. COUNTER STABILITY - χ^2 TEST

This check for overall stability of the counter indicates whether the counter is operating satisfactorily by showing that the variations in a number of statistical counts conform to normal statistical fluctuations. The formula used is

$$\chi^2 = \frac{\sum x_i^2 - \frac{(\sum x_i)^2}{10}}{\bar{x}} ,$$

where $\sum x_i^2$ = sum of the squares of ten individual observations,

$\sum x_i$ = the sum of ten individual observations, and

\bar{x} = mean of ten observations.

For stability, χ^2 must lie between 3.35 and 16.92.

