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**THE PELINDABA FACILITY FOR CALIBRATING  
RADIOMETRIC FIELD INSTRUMENTS**

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B. Corner  
P.D. Toens  
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ATOMIC ENERGY BOARD  
Pelindaba  
PRETORIA  
Republic of South Africa

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C.M. Vlegaar\*

\*Atomic Energy Board  
Private Bag X256  
PRETORIA 0001

\*\*Geological Survey  
Private Bag X112  
PRETORIA 0001

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## SAMEVATTING

Die geweldige uitbreiding in uraanopsporing gedurende die afgelope paar jaar het die behoefte aan die standaardisering en kalibrering van radiometriele veldinstrumente duidelik laat blyk. Om aan hierdie behoefte te voldoen, is daar in 1973 begin om 'n kalibreerfasiliteit by die Nasionale Kernnavorsingsentrum, Pelindaba, te bou. Dit is sedertdien volgens die vereistes van die mynbedryf uitgebrei.

Die fasiliteit bestaan tans uit 11 standaardbronne op die oppervlak waarmee draagbare sintillasiemeters en spektrometers, in terme van radio-elementkonsentrasies, gekalibreer kan word asook enkel-modelboorgatbronne vir uraan en torium wat die akkurate kalibrering van boorgatopname-instrumente vir spektrometriese en bruto telopnames moontlik maak. Draagbare kalium-, uraan- en toriumbronne is ook beskikbaar om lugspektrometer-stroopverhoudings te bepaal.

Die toepaslike fisies-chemiese eienskappe van die standaardbronne in hierdie verslag aangedui en die kalibreerprosedures en datareduksietegnieke aanbeveel. Voorbeelde van die situ-metings word verstrek, beide op die oppervlak en in die boorgat, wat toon dat die afgeleide kalibreringskonstantes radiometriele grade lewer wat gemiddeld tot binne 5% van die ware radio-elementkonsentrasies akkuraat is.

'n Tweede fasiliteit wat uit enkelboorgat- en oppervlakuraanbronne bestaan, is by Beaufort-Wes in die suidelike Karoo gebou.

## ABSTRACT

The tremendous upsurge in uranium exploration activity, experienced in recent years, has made the need for the standardisation and calibration of radiometric field instruments apparent. In order to fulfill this need, construction of a calibration facility at the National Nuclear Research Centre, Pelindaba, was commenced in 1972 and has since been extended according to the requirements of the mining industry.

The facility currently comprises 11 surface standard sources suitable for the calibration, in terms of radio-element concentration, of portable scintillometers and spectrometers, and single uranium and thorium model-borehole sources which make possible the accurate calibration of borehole logging instruments both for gross-count and spectrometric surveys. Portable potassium, uranium and thorium sources are also available for the purposes of establishing airborne-spectrometer stripping ratios.

The relevant physico-chemical properties of the standards are presented in this report and calibration procedures and data reduction techniques recommended. Examples are given of *in situ* measurements, both on surface and down-the-hole, which show that the derived calibration constants yield radiometric grades which are, on average, accurate to within 5% of the true radio-element concentrations.

A secondary facility comprising single borehole- and surface-uranium sources has also been constructed in Beaufort West in the southern Karoo.

## 1. INTRODUCTION

In view of the widespread occurrence of uranium in the Republic of South Africa, radiometric field instruments have been extensively employed in the course of prospecting operations. Initially, however, instrument responses were viewed rather qualitatively, resulting in the maximum amount of information in terms of the *in situ* concentrations of the natural radio-elements, potassium, uranium and thorium, not being obtained. The tremendous upsurge in uranium exploration activity which was experienced during the early 1970's and which currently prevails, has made the need for the standardisation and calibration of radiometric field-instrument responses apparent. In order to fulfill this need, construction of a calibration facility at the National Nuclear Research Centre, Pelindaba, was commenced in 1972 (Toens, *et al* 1973) and has since been extended according to the requirements of the mining industry.

The facility currently comprises eleven flat-cylindrical concrete pads containing known amounts of potassium, uranium and thorium, and makes possible the calibration of field spectrometers for quantitative *in situ* determinations of the three radio-elements. In addition the standardisation

of scintillometers in terms of a fixed unit, viz. equivalent uranium ( $eU_3O_8$ ), may also be achieved. Uranium and thorium borehole standards enable the accurate calibration of borehole logging instruments, both for gross-count and spectrometric surveys. Portable potassium, uranium and thorium sources have also been constructed for the purposes of calculating airborne-spectrometer stripping ratios.

In view of the extensive use of the facility, a secondary facility has also been constructed in Beaufort West, in the southern Karoo, where major exploration programs are being undertaken.

In this report, the construction and relevant physico-chemical properties of the standard sources are briefly described and recommended calibration and data-reduction procedures are discussed. Results are also given of *in situ* radio-element concentration determinations using field spectrometers and borehole logging units calibrated at Pelindaba.

## 2. CONSTRUCTION OF THE CALIBRATION FACILITY

### 2.1 Selection of a Suitable Site

The calibration facility is sited approximately 30 kilometres West of Pretoria at the National Nuclear Research Centre, Pelindaba, on Ongeluk lavas of the Pretoria Group. These rocks are characterised by a low background gamma-radiation level which was the basis for the siting of the facility. The outlay of the standard sources is shown in Figure 1

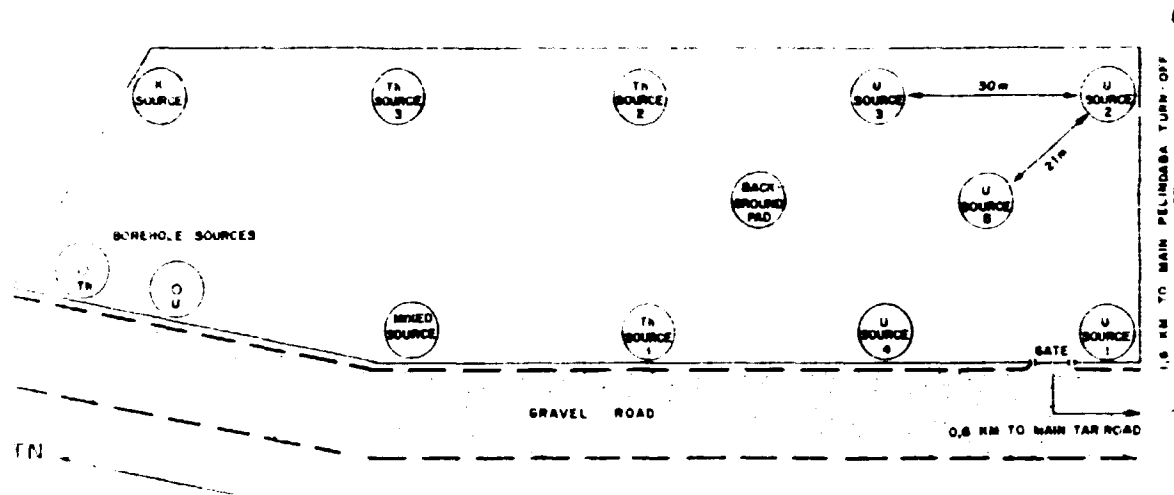


FIG 1 OUTLAY OF THE STANDARD SOURCES AT THE PELINDABA CALIBRATION FACILITY

### 2.2 Ore Selection

The uranium surface and borehole standards are composed of Reef ore (of the Upper Witwatersrand Subgroup) back-picked off the reef stockpile at the West Rand Consolidated Mine, Klerksdorp. With the aid of a wheel loader, the ore was sorted into four concentration categories weighing 2 t each and was crushed to 90% minus 20 mm prior to being transported to Pelindaba. The age, composition and depth (± 400 m) of the ore and host rock points to the uranium being in a state of secular equilibrium. This was subsequently supported by radiochemical analyses conducted on the ore at Pelindaba.

The potassium standards are composed of monazite ore derived from the defunct Steenkampskraal monazite mine near Vanrhynsdorp in the Western Cape. A potassium rich syenite, taken from the Brekerkop quarry in the vicinity of Phalaborwa, was used for the potassium source. The material used in the construction of the background pad was carefully selected, using a calibrated digital spectrometer in order that the concentrations of potassium, uranium and thorium would be an absolute minimum. The gabbro, derived from the Bushveld Igneous Complex, and clean quartz rich river sand were eventually selected for this purpose.

## 2.3 Construction of the Standard Sources

### 2.3.1 SURFACE STANDARD SOURCES

Calculations, utilising the PELSHE computer program (de Beer, 1971), showed that a cylindrical cemented pad of ore 2 m in diameter and 300 mm thick would suffice to simulate 98% of the gamma radiation due to a flat semi-infinite source, provided the detector be placed directly on the centre of the pad. This geometry was therefore used for all the surface standard sources, as also for the background pad.

All the standard sources were constructed in a similar manner, using between 2 and 2,5 t of ore material, building sand and cement, in varying proportions. In all cases the greatest possible care was taken to homogenise the ore/sand cement mix. This was particularly necessary for the uranium sources since the ore chips often varied considerably in uranium concentration. Homogenisation of the dry mix was checked through the use of a scintillometer or spectrometer and, when satisfactorily achieved, the mix was divided into a number of batches (4 - 5) for mixing in a concrete mixer. Each batch was then poured, to a thickness of 300 - 350 mm, into a metal cylinder 2 m in diameter and recessed to ground level. During pouring, 1 litre samples were taken from uniformly distributed points throughout the volume of the source for the purposes of subsequently establishing the concentrations of the three radio-elements in each source. A minimum of 10 samples were taken per source. The densities of the sources are estimated to be  $2,2 \pm 0,2 \text{ g.cm}^{-3}$  for the uranium sources and  $2,4 \pm 0,2 \text{ g.cm}^{-3}$  for all the other sources.

The calibration facility currently comprises one potassium, one mixed (U + Th), five uranium and three thorium surface standards, as well as a background pad. All the standards have been painted and their centres (reading points) indicated with a red dot.

### 2.3.2 BOREHOLE STANDARD SOURCES

Single uranium and thorium borehole standards are also available at the Pelindaba facility. Ore material similar to that described above was used. The two standards are of cylindrical geometry, being 1,1 m in diameter with a horizontal ore layer sandwiched between two radiometrically barren layers of concrete, and are penetrated centrally by a 110 mm hole. The uranium and thorium ore layers are 860 mm and 900 mm in thickness respectively. The standards are 2,2 m in length and are partially buried to make them easily accessible. The holes have been deepened into the bedrock to a depth of 5 m in order to accommodate long multi-system probes.

Great care was taken in the preparation of the respective layers of the sources both from the point of view of ore homogenisation and in order to avoid mixing of the wet ore- and barren-zones. BX and NX size steel casings and a PVC pipe (all sealed at one end) are available for use in the borehole standards, making possible the determination of calibration constants for a variety of borehole conditions, viz. dry holes, water-filled holes, cased dry holes and cased water-filled holes.

### 2.3.3 STANDARD SOURCES FOR AIRBORNE INSTRUMENTS

Portable standard potassium, uranium and thorium sources, which enable stripping ratios to be determined for airborne spectrometers, have been constructed and are available on a temporary loan basis to users throughout the country. They are cylindrical, measuring 0,25 m in diameter and 0,25 m in height, and comprise the same ore material as the other sources at Pelindaba except that KCl was used for the potassium source. The cement/ore mixes are sealed in aluminium cannisters for protection and also in order to avoid any radon loss from the uranium source.

In order to facilitate calibration in terms of radio-element concentrations, the Geological Survey utilises a calibration strip, situated approximately 10 km northwest of Oranjeville in the Orange Free State, on Karoo sediments of which the radio-element concentrations are accurately known (R.W. Day, 1978).

### 2.4 The Beaufort West Calibration Facility

In view of the extensive uranium exploration activity in the southern Karoo, it was decided in 1976 to construct a secondary facility in Beaufort West. The object was not that this should be an independent facility but rather that it should be a conveniently placed supplement to the main facility at Pelindaba. It is recommended that all instruments should initially be calibrated at Pelindaba and that the Karoo sources be used for the subsequent checking of instrument responses.

The Beaufort West facility comprises single uranium borehole and surface standard sources. They are of identical geometry to the Pelindaba sources, and similar construction procedures and ore were used. The borehole source is of a much lower concentration than its Pelindaba counterpart, in order to provide a double check on the derived calibration constant, and hence on the linearity of instrument responses, at medium to low grades. The ore layer of the borehole source is 0,95 m thick.

### 2.5 Homogeneity of the Surface Standards

The homogeneity of the surface standards was checked by reading the sources radiometrically using a lead-shielding technique. The technique involved placing a cylindrical lead block 80 mm thick and 80 mm in diameter in front of the detector probe on the reading point. Two readings were then taken, one with the lead block in position and one with the lead block replaced by a hollow polyester cannister of identical dimensions. The difference between the two readings relates to a conical volume of material directly below the position of the lead block and is largely independent of the rest of the source.

Readings were taken on a 200 x 200 mm grid on each of the surface standards and the results are presented in Fig. A1 in Appendix I. An inspection of the standard deviations given shows that variations in concentration for the first three uranium sources are within 10 % of the average values for each of these sources, whereas the variations for the fourth uranium source and for the three thorium sources are higher, being between 12 % and 17 %. However, since a large percentage of the gamma yield measured is derived from the central portion of a pad the mean of the central nine readings was compared with the overall mean value for each pad. In all cases, with the exception of the fourth uranium source, the discrepancy was less than 5 % indicating these sources to be adequately homogenous. The high discrepancy (10 %) for the fourth uranium source necessitated modification of the adopted concentration of this pad.

## 3. RADIO-ELEMENT CONCENTRATIONS OF THE PELINDABA STANDARD SOURCES

### 3.1 Analytical Results

The accuracy of any radiometric field instrument is dependent on a number of factors such as disequilibrium, source geometry, energy calibration etc., but rests ultimately with the accuracy of the radio-element concentrations determined for the standard sources used in calibrating the instrument. It is unfortunate, therefore, that discrepancies often occur between the analytical results presented by various laboratories in determining the radio-element concentrations. This problem, which is of a universal nature, has hampered the choice of radio-element concentrations for the standard sources at Pelindaba.

The samples taken during the construction of the standard sources, were milled and forwarded to the following analytical laboratories for determination of the concentrations of one or more of the three radio-elements: The National Institute for Metallurgy (NIM), General Mining and Finance Corp. Ltd (GEN. MIN.), Rio Tinto Zinc Corp Ltd (RTZ) and the Isotopes & Radiation and Chemistry Divisions of the Atomic Energy Board (AEB).

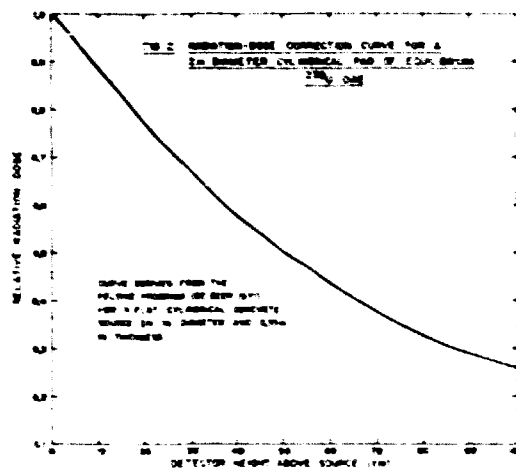
The analytical methods used included delayed-neutron, radiometric (laboratory), chemical, colorimetric, X-ray fluorescence, atomic-absorption-spectrophotometric and neutron activation techniques. Both local and international standards were used to check the accuracies achieved. The results thus obtained are presented in Table I.

### 3.2 Source Concentrations

In assessing the analytical results it was decided to calculate the mean values of the concentrations given by the various laboratories and to use these as a basis for the absolute source concentrations. Slight modifications were necessary, within the limits of the standard deviations involved, based on source inhomogeneities and the linearity of the concentrations when related to instrument responses.

In calculating stripping ratios and calibration constants for an instrument, the count-rate/radio-element-concentration response function must be accurately known. This usually linear function involves only three data points for the three thorium sources and four data points for the uranium sources. In view of the inevitable minor inhomogeneities in the standard sources (reflected by the lead-shielding results in Appendix I and the standard deviations in Table II) and the possibility that certain instruments may be non-linear, these data were considered to be insufficient. It was therefore decided that radiation from the sources should be observed directly on the centre of the source and at three heights (0,25 m, 0,5 m and 1,0 m) directly above it. The benefits derived from this procedure are, firstly, that additional data points would be available in the linear regression analysis thus improving the statistics; secondly, improved definition of the response function of non-linear instruments would be achieved; and thirdly, any inhomogeneities would be smoothed out since, by raising an instrument above the source, a larger volume of the source would contribute to the instrument response.

Obviously, as soon as an instrument is raised above a pad of the dimensions given, the pad ceases to be a semi-infinite source due to the increased detector cone-of-influence. A computer program, PELSHIE, developed at Pelindaba (de Beer, 1971) enables correction factors to be applied to the source concentrations for various source-detector distances. This effectively reduces the instrument/source configuration to a semi-infinite ground-level situation providing four data points per source in the regression analysis. A concentration correction curve, derived from expected exposures from an equilibrium  $^{238}\text{U}$  ore in a concrete matrix for source detector distances varying from 0 to 1,0 m, is shown in Fig. 2.



After numerous instrument calibrations at Pelindaba, however, it was observed that the correction factors derived from this curve for various heights above the sources were not entirely consistent with the true source concentrations. It was found that, for measurements made in the total-count channel, the correction factors were excessive, whereas for spectrometer responses they were marginally low. The result was a slight scatter of data points which initially was thought to be due entirely to the inhomogeneity of the sources. It was apparent, therefore, that the PELSHIE derived correction curve was inadequate to describe accurately the relative concentrations of the sources for the various energies and heights being observed, but could nevertheless be used as a first approximation in the derivation of these concentrations. The reason for this discrepancy may lie in the fact that the count rates to be expected at the various heights are not necessarily entirely equivalent to the expected exposure rates. These observations were supported by correction curves given by Løvborg *et al* (1972) for source detector distances of 0 - 150 mm.

In order to establish instrument response-function curves of improved definition, the responses of 10 different spectrometers and 10 scintillation meters were accurately noted for each source, particular attention being paid to counting statistics. Mean deviations from linearity, based on the true source concentrations, were determined and new concentration correction factors calculated at the various reading heights.

The finally adopted concentrations, thus derived, are presented in Table II. Values quoted at 0 mm are true concentrations, based on the analyses in Table I with slight modifications due to the observed inhomogeneities, and those quoted at 0,25 m, 0,5 m and 1,0 m are relative concentrations as derived above. The two sets of concentrations, viz. for the total-count channel and for the uranium and thorium channels, differ slightly from the single set of values previously published (Corner & Toens, 1979) and, although they will yield instrument response functions of improved definition, they should not affect previously derived calibration constants by more than 5%.

**TABLE I  
RADIO-ELEMENT CONCENTRATIONS IN THE STANDARD SOURCES : ANALYTICAL RESULTS**

LABORATORY	METHOD	ANALYSIS (g/l)	SURFACE STANDARDS								BOREHOLE STANDARDS		
			U-SOURCE 1	U-SOURCE 2	U-SOURCE 3	U-SOURCE 4	U-SOURCE 5	K-SOURCE	BACKGROUND PAD	U-SOURCE (BEAUFORT WEST)	U-SOURCE	Th-SOURCE	U-SOURCE (BEAUFORT WEST)
AEB	Delayed Neutron	U <sub>3</sub> O <sub>8</sub>	4 382 ± 376	2 547 ± 412	1 487 ± 163	478 ± 158	17 ± 3	< 0.5	0.7 ± 0.2	1 360 ± 266		22 ± 4	160 ± 74
	Radiometric (NAA, DN)	ThO <sub>2</sub>	418 ± 183	244 ± 80	153 ± 47	53 ± 21	< 10(DN)	< 10	< 10(DN)	85 ± 12(NAA)			18 ± 8
	Chemical	K <sub>2</sub> O (%)	0.35	0.40	0.35	0.47	0.40 ± 0.04		0.40 ± 0.04	0.14 ± 0.04		0.81 ± 0.10	0.28 ± 0.06
RTZ	Chemical	U <sub>3</sub> O <sub>8</sub>	4 374 ± 381	2 633 ± 453	1 484 ± 167	637 ± 107							
NIM*	Colorimetric (XRF)	U <sub>3</sub> O <sub>8</sub>	4 200	2 570	1 560	570		5.0(XRF)			1 530 1 440 ± 236		
	Colorimetric (XRF)	ThO <sub>2</sub>	330	230	130	80		20.0 ± 4.0(XRF)			134 ± 14(XRF)	1104 ± 176	
	AA Spectrophotometry	K <sub>2</sub> O (%)	0.26	0.27	0.20	0.26		12.2			0.86		
GEN. MIN.	Chemical	U <sub>3</sub> O <sub>8</sub>	3 898 ± 348	2 339 ± 384	1 421 ± 149	528 ± 94							
	Radiometric	U <sub>3</sub> O <sub>8</sub>	4 143 ± 388	2 461 ± 390	1 527 ± 198	553 ± 125							

LABORATORY	METHOD	ANALYSIS (g/l)	SURFACE STANDARDS				AIRBORNE STANDARDS			
			Th-SOURCE 1	Th-SOURCE 2	Th-SOURCE 3	MIXED SOURCE	U-SOURCE	Th-SOURCE	K-SOURCE	
AEB	Radiometric	ThO <sub>2</sub>	14 594 ± 282	4 105 ± 429	3 898 ± 521					
	Chemical	K <sub>2</sub> O (%)					0.54 ± 0.14	1.90 ± 0.02	63.0	
NIM*	XRF	ThO <sub>2</sub>	14 320 ± 610	4 308 ± 184	3 496 ± 299	4 280 ± 314	150 ± 25	10 666 ± 172		
	XRF	U <sub>3</sub> O <sub>8</sub>	326 ± 18	115 ± 12	78 ± 10	848 ± 200	1 747 ± 230	160 ± 6		
	XRF(Composite)	ThO <sub>2</sub>	14 610	4 600		4 700				
	XRF(Composite)	U <sub>3</sub> O <sub>8</sub>	321	108		833				
	Colorimetric	ThO <sub>2</sub>	14 600	4 000		4 200				
	Colorimetric	U <sub>3</sub> O <sub>8</sub>	391	119		902				

\* Standard deviations of analyses on 10 or more samples, where no standard deviations are given analyses were conducted on composite samples

\* Analytical reports of the National Institute for Metallurgy Project reports 80411(1), 80541(1), 80473(1,2), 61078(1) and 83176(1)



**TABLE II**  
**RADIO-ELEMENT CONCENTRATIONS IN THE STANDARD SOURCES : ADOPTED VALUES**

STANDARD SOURCES	HEIGHT ABOVE SOURCE (m)	K <sub>2</sub> O (%)	U <sub>3</sub> O <sub>8</sub> (g/t)		ThO <sub>2</sub> (g/t)
			TOTAL COUNT	U and Th CHANNELS	
Uranium - Pad 1	0	0.35	4 400	4 400	374
	25		3 220	3 130	256
	50		2 350	2 170	180
	100		1 220	1 080	92
Uranium - Pad 2	0	0.40	2 480	2 460	237
	25		1 810	1 690	162
	50		1 310	1 140	114
	100		690	580	58
Uranium - Pad 3	0	0.35	1 490	1 490	142
	25		1 110	1 030	97
	50		820	740	68
	100		430	380	35
Uranium - Pad 4	0	0.47	530	530	51
	25		410	370	35
	50		300	270	25
	100		170	140	13
Uranium - Beaufort West Pad	0	0.14	1 360	1 360	85
	25		1 000	950	58
	50		730	663	40
	100		380	340	21
Thorium - Pad 1	0	< 1.0	326	326	14 200
	25		240	228	9 700
	50		175	160	6 700
	100		92	82	3 450
Thorium - Pad 2	0	< 1.0	115	115	4 250
	25		85	80	2 900
	50		62	56	2 020
	100		32	29	1 030
Thorium - Pad 3	0	< 1.0	76	76	3 500
	25		56	53	2 410
	50		41	37	1 720
	100		21	19	880
Mixed Uranium, Thorium Pad	0	< 1.0	850		4 400
Uranium - Pad 5	0	0.40	17		< 10
Potassium Pad	0	12.2	< 0.5		< 10
Background Pad	0	0.40	0.7		< 10
Borehole Uranium Source - Pelindaba		0.96	1 440		134
Borehole Thorium Source - Pelindaba		0.61	22		1 104
Borehole Uranium Source - Beaufort West		0.28	150		16
Airborne Spectrometer - Potassium Source		63.0			-
Airborne Spectrometer - Uranium Source		0.54	1 750		150
Airborne Spectrometer - Thorium Source		1.90	160		10 670

## 4. RECOMMENDED CALIBRATION PROCEDURES AND DATA REDUCTION

### 4.1 Portable Total-Count Instruments

The standardisation of all scintillometer responses, in terms of a single meaningful unit of reference, is essential in uranium exploration, firstly in view of the often widely varying sensitivities of different instrument makes, and secondly since most instruments are graduated in terms of a gamma count rate which, without any conversion, is relatively meaningless from a geochemical point of view. Such a unit is *equivalent uranium (eU<sub>3</sub>O<sub>8</sub>)*, indicating the concentration of U<sub>3</sub>O<sub>8</sub> which would account for the observed reading, if no potassium or thorium were present. This obviously still suffers from the inherent limitation that total count instruments are non-discriminative and thus the eU<sub>3</sub>O<sub>8</sub> value will only reflect the true U<sub>3</sub>O<sub>8</sub> concentration if an occurrence is known by some other means to contain uranium only (and other factors such as correct geometry and equilibrium are assumed - see Section 5).

#### 4.1.1 CALIBRATION PROCEDURE

In order to establish the eU<sub>3</sub>O<sub>8</sub> response for a total count instrument at Pelindaba, it is recommended that the uranium standards 1 - 4 be read directly on the centre of each pad (indicated by a red dot) and at heights of 0,25, 0,50 and 1,00 m above it. An aluminium stand is provided for this purpose. If the instrument is equipped with a rate meter and has an external time-constant facility, it is recommended that this should be set to a high value (3 - 10 s) in order that improved average values may be obtained. For digital scintillometers a minimum of five readings should be averaged per height for a sample period of 1 s; this number can be reduced if the sample period is increased. Readings should also be taken (at 0 mm only) on the background pad.

The count rates are then plotted against the corresponding U<sub>3</sub>O<sub>8</sub> concentrations given in Table II. The small quantities of ThO<sub>2</sub> in the uranium sources will obviously affect the observed count rates and hence the eU<sub>3</sub>O<sub>8</sub> values. This effect is, however, expected to be less than 5% and, if greater accuracy is required, it is recommended that the thorium sources be read in order to establish the instrument count rate per unit g/t ThO<sub>2</sub>. A correction may then be applied either by using the formulae given in Appendix II, or by reduction of the data at the Pelindaba Computer Centre.

The resultant response function thus provides a means for standardising the instrument in terms of eU<sub>3</sub>O<sub>8</sub>. If linear, a calibration constant can be calculated from the slope of the graph by which all field readings can be multiplied. Where the instrument deviates from linearity (usually at higher concentrations) the field worker will have to refer to the graph for an eU<sub>3</sub>O<sub>8</sub> value. Thus eU<sub>3</sub>O<sub>8</sub>(g/t) = K<sub>1</sub>X field count rate (background corrected) where K<sub>1</sub> is the slope of the calibration graph in terms of g/t eU<sub>3</sub>O<sub>8</sub> per unit cps.

Total-count calibration data may be plotted at the Pelindaba Computer Centre. Calibration data sheets of which an example is given in Appendix III, are obtainable from the Geology Division. In order to assist the field geologist even further, a local manufacturer will produce scintillometers graduated directly in terms of g/t eU<sub>3</sub>O<sub>8</sub>, as derived at the Pelindaba facility, rather than in counts per second.

### 4.2 Portable Spectrometers

The calibration procedure for portable spectrometers is essentially the same as for scintillometers. Uranium sources 1 - 4 and the three thorium sources should also be read centrally at the four standard heights, whereas the potassium and background pads should be read directly on their surfaces. (Readings at various elevations above the latter two pads are not recommended, firstly since they are both extremely homogeneous, and secondly since counting statistics would be poor and hence contributions from the surrounding soil and rock might be significant.) It is important to note that good counting statistics are essential for an accurately calibrated spectrometer. Instruments equipped with ratemeters should be read using a long time-constant and digital spectrometers should be read a minimum of three times per height for a sample period of at least 10 s. Where low count rates are encountered the number of readings and/or the sample period should be increased.

It must be stressed that whenever any quantitative spectrometer surveys are conducted, including calibration, energy-window alignment (loosely termed 'energy calibration' by most manufacturers) must be continuously checked according to manufacturers' instructions. For some instruments this might be as frequently as every half-hour, depending on local changes in temperature.

The 'cool' 5th uranium source and the mixed source may be used as checks on the validity of the calibration equations (5) below. The former source may be of particular use to geologists mapping with the aid of a spectrometer in areas of relatively low uranium concentration.

#### 4.2.1 REDUCTION OF THE CALIBRATION DATA

The calibration constants which relate the observed count rates to ground concentrations of potassium, uranium and thorium are calculated by solving a series of linear simultaneous equations (Richards, 1976) which are set up as outlined below. Similar matrix-based methods of calibration-data reduction have been reported, e.g. Løvborg *et al* (1972).

The count rate y<sub>ij</sub> in any channel i due to source j is given by

$$y_{ij} = a_1x_{j1} + a_2x_{j2} + a_3x_{j3} \dots \dots \dots (1)$$

where

- a<sub>1i</sub> = count rate in i<sup>th</sup> channel per unit per cent potassium
- a<sub>2i</sub> = count rate in i<sup>th</sup> channel per unit g/t uranium
- a<sub>3i</sub> = count rate in i<sup>th</sup> channel per unit g/t thorium

and

- x<sub>j1</sub> = percentage K<sub>2</sub>O in source j
- x<sub>j2</sub> = g/t U<sub>3</sub>O<sub>8</sub> in source j
- x<sub>j3</sub> = g/t ThO<sub>2</sub> in source j

In matrix notation, these equations may be written as  $Y = X A$

where

- Y = the matrix of observed count rates
  - X = the matrix of source compositions
  - A = the matrix of calibration constants
- (As in normal matrix notation, the subscript convention above is that the first subscript of each element refers to the row, and the second subscript to the column of the matrix where the element occurs.)

In pictorial form:

$$m \begin{matrix} n \\ \boxed{Y} \end{matrix} = m \begin{matrix} 3 \\ \boxed{X} \end{matrix} \cdot 3 \begin{matrix} n \\ \boxed{A} \end{matrix} \dots \dots \dots (2)$$

where m is the number of sources used and n is the number of spectrometer channels (n=3 for most portable spectrometers and m=7 for the Pelindaba facility, i.e. four uranium and three thorium sources all with varying concentrations of these two elements).

To solve these equations for the required calibration constants, readings must be taken over at least three sources with different known compositions. If more than three sources are used, as at Pelindaba, the variables are overdetermined and the equations are solved using a least squares criterion. Retaining the matrix notation, the set of equations  $Y = X A$  thus has the least-squares

$$\text{solution } A = (X^T X)^{-1} X^T Y \dots \dots \dots (3)$$

Thus, knowing the observed count rates and the source compositions, the calibration constants (represented by the matrix A) can be calculated.

The established computer program (after Richards, 1976) utilised at Pelindaba, first normalises the observed counts to unit counting time (i.e. converts them to count rates) and makes a correction for the observed background. The matrix of calibration constants (A) is then calculated as above by simple matrix manipulation. Since the potassium count rates are very low and since the Pelindaba uranium and thorium sources contain relatively small amounts of potassium, it has been found convenient to calculate the potassium constants separately.

The matrix approach has been adopted because it is readily generalised to arbitrary numbers of sources and arbitrary numbers of spectrometer channels. In addition, most modern computers have available subroutines which perform matrix operations quickly and efficiently, and which minimise programming requirements.

**4.2.2 USE OF CALIBRATION CONSTANTS**

Once the calibration constants have been calculated, the spectrometer may be used to make quantitative determinations of potassium, uranium, and thorium in the field. The matrix equation  $Y = X A$  will still describe the field situation, but in this case X, the source composition matrix, is the unknown. For a 3 channel spectrometer which is being used at a single field point, m = 1 and n = 3. Thus Y is simply the row vector of observed count rates (corrected for background and normalised to unit counting time) in the potassium, uranium and thorium channels. A is the square matrix of calibration constants, and X, the row vector of source compositions, is calculated from:

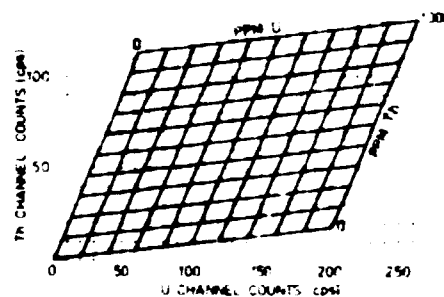
$$X = Y A^{-1}$$

If more than three spectrometer channels are used, a least-squares criterion may again be used and

$$X = Y A^T (A A^T)^{-1} \dots \dots \dots (4)$$

For convenience, a calibration chart such as shown in Fig. 3 may be drawn from elements a<sub>22</sub>, a<sub>23</sub>, a<sub>32</sub> and a<sub>33</sub> of the calibration matrix (A), this allows uranium and thorium concentrations to be obtained quickly in the field.

**FIGURE 3**  
**ATOMIC ENERGY BOARD / GEOLOGICAL SURVEY**  
**GAMMA-RAY SPECTROMETER CALIBRATION CHART**



Calibration data are reduced at the Pelindaba Computer Centre and the corresponding calibration charts are plotted as a free service to industry. The matrices of calibration constants, (A) and inverse (A<sup>-1</sup>), are also given and, if the calibration chart is found not to be sufficiently accurate (due to its scale), the potassium, uranium and thorium concentrations may be calculated directly from the inverse matrix as follows:

If the inverse matrix  $A^{-1}$  is given by

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$$

then

$$\left. \begin{aligned} K_2O.g.t. &= a_{11}(K) + a_{12}(U) + a_{13}(Th) \\ U_3O_8.g.t. &= a_{21}(K) + a_{22}(U) + a_{23}(Th) \\ ThO_2.g.t. &= a_{31}(K) + a_{32}(U) + a_{33}(Th) \end{aligned} \right\} \dots \dots \dots (5)$$

where (K), (U) and (Th) are the count rates, normalised to unit counting time, in the potassium, uranium and thorium channels respectively.

Calibration data sheets for spectrometers as well as for total count instruments are available at the Geology Division, Peindaba. An example is presented in Appendix III. Five readings per observation point are allowed for the uranium and thorium sources and ten readings are allocated for the background and potassium pads. If accurate counting statistics are required, counting times should be increased above the minimum sample periods recommended in Sections 4.1 and 4.2.

### 4.3 Borehole Logging Instruments

The calibration procedure and method of analogue field log interpretation presented here are based on the 'total area' method of Dodd and Eschliman (1972). The procedure is simple, accurate and can be readily applied to raw data either manually in the field or by computer analysis using a program such as GAMLOG (Dodd & Eschliman, 1972).

A more sophisticated interpretation approach utilising digital time series analysis may be used (Conway and Killeen, 1978). Inverse digital filters are applied to the data using discrete convolution in order to produce a log giving radio element concentration (discriminated where required) as a function of depth. Although analogue gamma logs may be readily digitised, this involves added costs, and digital (incremental) gamma logging, which is not currently being employed in South Africa, is therefore ideally suited to this approach. Access to a microprocessor or portable minicomputer is also necessary for on-line data processing and, unless large scale logging programs with high daily production rates are envisaged, costs might make this approach unattractive. In addition the effectiveness of the deconvolution procedure diminishes with decrease in count rate and corresponding increase in the statistical noise envelope - an inherent problem with many of the low-tenor local uranium ores.

### 4.3.1 CALIBRATION PROCEDURE: TOTAL-COUNT LOGGERS

The Peindaba uranium borehole standard and corresponding total-count gamma log is schematically shown in Fig. 4(a). Prior to being calibrated, the logging system should be allowed a warm-up period and the energy-window alignment checked according to manufacturer's instructions, where necessary. For calibration from an analogue chart such as in Fig. 4(a) the detector probe should be lowered at a speed of 1 m.min<sup>-1</sup> with a time constant setting of 1 or 2 s. This will produce an expanded anomaly suitable for the derivation of a calibration constant. With digital calibration, required for computerised interpretation methods, measuring intervals of between 100 and 50 mm should be used (depending on the accuracy required), due attention being paid to an adequate counting time.

FIG 4a BOREHOLE CALIBRATION PEINDABA

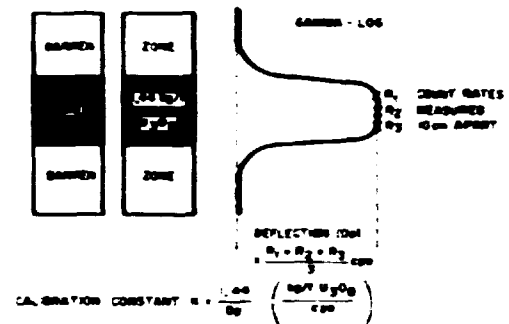
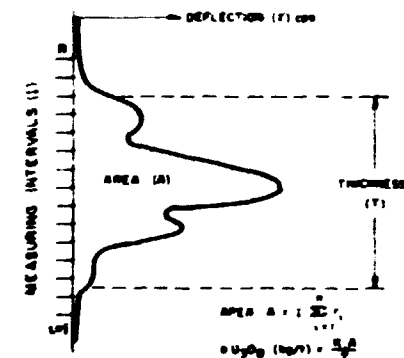


FIG 4b INTERPRETATION OF FIELD LOG



The instrument calibration constant (or K factor) may be derived in one of two ways, viz.:

(1) By the Plateau Method

$$K = \frac{1.44}{D_p} \left[ \frac{kg/t U_3O_8}{cps} \right] \dots \dots \dots (6a)$$

where  $D_p$  is the average maximum deflection, from the zero line, of the log and should be calculated by averaging at least three count rates 100 mm apart ( $R_1$ ,  $R_2$  and  $R_3$ , or more, at closer intervals) in the central plateau region of the

anomaly. For the Beaufort West borehole standard, which is thicker, the 'plateau' should be averaged over 400 mm (i.e. five count rates 100 mm apart in the central plateau region) in view of the inhomogeneity of this source.

(ii) By the Total-Area Method

$$K = \frac{1.44}{D_a} \left[ \frac{\text{kg/t } U_3O_8}{\text{cps}} \right] \dots \dots \dots (6b)$$

where  $D_a$  is the maximum deflection calculated from the relation

$$D_a = \frac{\text{Anomaly Area (A')}}{\text{Ore-zone thickness}}$$

A' is the area under the calibration anomaly approximated by numerical integration as follows:

$$A' = l \cdot \sum_{i=1}^n r_i \dots \dots \dots (6c)$$

where  $r$  is the equivalent count rate deflection for the  $i$ th interval and  $l$  is the measuring interval used.

The deflections  $D_a$  and  $D_p$  are numerically equal and will thus yield the same  $K$  factor. The total-area method may be used in preference for digital systems and should provide a more accurate  $K$  factor for calibration standards which are not perfectly homogeneous and therefore do not have a perfect plateau region (e.g. the Beaufort West source).

$K$  factors may be determined using either of the above methods for a variety of shielding media in boreholes, viz. air, water, casing and casing plus water. BX- and NX-sized casings are available at the facility for this purpose. Users are requested not to pour water directly down the holes. A PVC pipe (NX diameter = 80 mm) sealed at one end (as are the casings) is available for this purpose.

$K$  factors calculated in this way using the Atomic Energy Board's logging unit have been found to agree within 3%, i.e. within the limits of experimental accuracy, for the Pelindaba and Beaufort West borehole standards.

**4.3.2 FIELD-LOG INTERPRETATION**

The analogue field record may be converted to  $eU_3O_8$  concentration either manually or by computer as follows (ref. Fig. 4(b)), the area under the curve is approximated by numerical integration in exactly the same way as with the total area method of calibration, i.e. the field log is divided up uniformly into measuring intervals of not more than 100 mm (this may be reduced to 50 mm for greater accuracy with anomalies of narrow half-amplitude width). The deflections at each of the measuring points, in terms of count rates, are then summed from background to background, and multiplied by the measuring interval (refer to equation 6c). This yields the area under the field curve (A) and the equivalent  $U_3O_8$  concentration is given by

$$eU_3O_8 \text{ (kg/t)} = \frac{K \cdot A}{T} \dots \dots \dots (7)$$

where  $T$  is the thickness of the mineralised zone calculated from half-amplitude points of the first and last anomalies as in Fig. 4(b). For this relation to be valid  $T$  should be greater than  $\pm 500$  mm otherwise inaccuracies due to the effect of thinness dilution will result (see Section 5.1.1).

Past users of the Pelindaba facility will notice that the definition of the calibration constant ( $K$ ) has changed in that it is no longer multiplied by the measuring interval. This is in accordance with the recommendations of Fink (1978) made on the use of  $K$  and  $A$  at the Grand Junction Calibration Facility, USA, viz. since  $K$  is a constant of proportionality relating uranium concentration to count rate it should not be dependent on the measuring interval. Similarly, the anomaly area is not correctly defined unless it is multiplied by the measuring interval employed. However, incorporating  $l$  in  $A$  rather than in  $K$  has no effect on the final  $eU_3O_8$  determination.

The accuracy of the  $eU_3O_8$  concentrations derived, using a calibration model, is obviously dependent on a number of factors such as instrument dead-time, thinness dilution, disequilibrium and the accuracy with which the model simulates field conditions. These aspects are discussed in Section 5.

**4.3.3 CALIBRATION PROCEDURE: SPECTROMETER LOGGERS**

In order to be able to determine uranium and thorium concentrations quantitatively down-the-hole, calibration constants must be derived from both the uranium and thorium borehole standards. These should be logged in the uranium and thorium channels in the same way as described in the preceding discussion. Two factors are, however, of utmost importance both in calibrating and in field surveys: firstly, since the signal-to-noise ratio deteriorates drastically due to the narrow energy windows, adequate counting statistics must be achieved by either increasing the counting time or reducing the probe speed; and secondly, correct energy-window alignment must be maintained by utilising the alignment source supplied with the instrument. In field surveys the alignment is best achieved by first conducting a reconnaissance log of the borehole in order to locate the mineralised zone. By this time the detector probe will have attained the average temperature in the hole and should then be readjusted for energy-window alignment prior to logging the mineralised zone in detail. Some of the latest instruments are drift-stabilised by means of a built-in source and this procedure then becomes unnecessary.

Calibration constants may be calculated in the same way as for hand-held spectrometers in the preceding section, i.e. referring to equation (1), and neglecting the minor amounts of potassium in the two sources, four simultaneous equations may be set up expressing the maximum deflections (central plateau region of the anomaly, see Fig.

4(a) of the uranium ( $U_1$  and  $U_2$ ) and thorium ( $Th_1$  and  $Th_2$ ) channels in terms of the source concentrations as follows:

For the uranium source,

$$U_1\text{cps} = a_{21} \times x_{12} + a_{31} \times x_{13}$$

$$Th_1\text{cps} = a_{22} \times x_{12} + a_{32} \times x_{13}$$

and for the thorium source

$$U_2\text{cps} = a_{21} \times x_{22} + a_{31} \times x_{23}$$

$$Th_2\text{cps} = a_{22} \times x_{22} + a_{32} \times x_{23}$$

where  $x_{12}$  and  $x_{13}$  are the concentrations of  $U_3O_8$  and  $ThO_2$  in the uranium source respectively,

$x_{22}$  and  $x_{23}$  are the concentrations of  $U_3O_8$  and  $ThO_2$  in the thorium source respectively.

and  $a_{21}$ ,  $a_{31}$ ,  $a_{22}$  and  $a_{32}$  are the calibration constants, in terms of count rates in the uranium and thorium channels per unit concentration of  $U_3O_8$  and  $ThO_2$ , defining the matrix A.

The required calibration constants in terms of concentration per unit count rate may then be calculated from the inverse of  $A = (X^T X)^{-1} X^T Y$ .

Borehole calibration data may be reduced in this manner at the Pelindaba Computer Centre. Users are requested to utilise the data sheets, of which an example is given in Appendix IV, obtainable at the Geology Division.

The question of background counts is worthy of mention here since any observed count rate should, strictly speaking, be corrected for background. However, since cosmic radiation is completely attenuated by the rocks surrounding the probe in a borehole, the only background measured will be due to inherent instrument noise. For most loggers this is extremely low and absolute background may be considered negligible. Although there is no facility at Pelindaba for readily determining the absolute background of loggers, a close approximation may be obtained by lowering the detector probe to the bottom of the calibration holes, i.e. into the Ongeluk lava which contains only trace amounts of uranium and thorium and small amounts of potassium (the latter being of extremely low activity anyway).

#### 4.4 Airborne Spectrometers

The calibration of airborne spectrometers is ideally achieved through the use of large pads with a recommended (IAEA 1976) minimum diameter of 8,0 m. In executing the large-scale airborne survey of the Karoo Basin, which covers roughly 60% of the Republic, time did not permit the construction of such sources. In addition it was considered impractical logistically for the aircraft to return continually to a central facility for calibration checks. The portable cylindrical sources described in Section 2.3.3 were thus constructed as a compromise. They enable stripping ratios to be calculated, in much the same way as for portable spectrometers, and the reader is referred to Richards

(1977,1978) and Day (1977) for the procedure. They do not, however, permit the accurate determination of radio-element concentration in the area surveyed. In order to facilitate this, the Geological Survey currently utilises a test airstrip on Karoo sediments of which the radio-element concentrations are accurately known.

## 5. ACCURACY OF *IN SITU* RADIOMETRIC ASSAYING

### 5.1 Factors Affecting Accuracy

The accuracy of any *in situ* radiometric assay, assuming adequate counting statistics, is dependent on numerous factors of which the most important are true simulation of field conditions by the calibration model, the presence of thorium or potassium in the case of non-discriminating instruments, geometry, disequilibrium and instrument dead-time. Detailed discussion of these factors is beyond the scope of this paper and only the essentials will be repeated in order to retain the reader's awareness of the problems and limitations involved. Further details may be found in the quoted references.

#### 5.1.1 GEOMETRY AND CALIBRATION-SOURCE CHARACTERISTICS

The calibration facility at Pelindaba simulates essentially two geometries encountered in the field, viz. a  $2\pi$  steradian (flat semi-infinite surface) geometry and a  $4\pi$  steradian geometry as encountered in a borehole. Any deviations from these geometries may result in serious errors in predicted radio-element concentration. In the field a good  $2\pi$  steradian geometry is considered to be one where the outcrop being checked is reasonably flat for a radius of 1 m around the detector probe (with the probe placed on the outcrop). If the observation point is in a gully or valley or next to a hill, optimistic radiometric grades will be measured due to side effects, unless the surrounding rock is essentially barren from a radio-element point of view. This can be overcome both on surface and underground through the use of a lead-block shielding technique, such as used to check the homogeneity of the standard sources, described in Section 2.5 (Corner, 1978). Conversely, if the outcrop or boulder being checked is smaller than the calibration pads, a pessimistic radiometric grade will result. Deviation from the calibration geometry may thus result in errors of hundreds of per cent or more.

The problem of geometry is not as severe with borehole instruments since most boreholes are of a regular and easily simulated geometry. Variations in borehole diameter may, however, lead to marked errors in radiometric-grade determinations, especially for water-filled holes where the shielding effect of water plays an important role (Dodd and Eschliman, 1972). The 110 mm holes at the Pelindaba facility are a good compromise for most exploration holes, and any deviations from this diameter, within the range 70 - 150 mm for water-filled holes, should result in errors

of not greater than 5% for most detector probes. A similar accuracy may be achieved in dry holes for a slightly larger diameter range. It is nevertheless intended to construct additional borehole sources with varying hole diameters in order to be able to determine diameter correction factors.

A further geometric effect in boreholes is one of thinness dilution where an intersected ore layer, very much thinner than the diameter of the sample-volume spheroid (i.e.  $\leq 500$  mm), will result in an underestimation of radiometric grade and an overestimation of layer thickness. This problem can be overcome if a convolution interpretational procedure is applied (Conaway and Killeen, 1978) or alternatively if correction curves are utilised (Corner and de Beer, 1976).

Radon loss from the calibration sources could also seriously affect the calibration constants, and hence the resultant *in situ* radio-element determinations, yielding optimistic results. Such radon loss has been reported (Løvborg *et al*, 1978) at the Risø calibration facility in Denmark. Radon escape-production ratios have been determined on a small number of the ore chips used at Pelindaba and were found to be small, varying between 2 and 7%. Inspection of the results in the following section lead one to the conclusion that any effects of radon loss are thus negligible at Pelindaba. This is further supported in that continuous monitoring of the sources since 1973 has shown no marked seasonal variations in gamma activity such as reported at Risø. It is felt that the size of the ore chips played an important part in reducing the effect of radon loss. Contrary to subsequent recommendations of the IAEA (Report 174, 1976) that the ore material should be crushed to the consistency of sand, the ore at Pelindaba was crushed only to 90% minus 20 mm. Each ore chip, which comprises highly consolidated quartzite or conglomerate, may thus be considered as a sealed unit allowing a small percentage of radon to escape only from the uranium minerals (uraninite) appearing at the surface.

In using a coarse aggregate for the ore material, however, the overall density of the sources is reduced and is therefore somewhat less than the average values for most rocks (see Section 2.3.1). Løvborg *et al* (1972, p. 157) have shown that gamma-spectrometer calibration constants are essentially independent of rock density and chemical composition for most rocks. Intuitively, one might expect a higher count rate from a rock of relatively low density, due to a reduction in the attenuation of the gamma rays. This would, however, be compensated by the fact that an equal volume of rock of lower density, given a fixed concentration per unit mass, would contain less uranium, thus reducing the observed count rate. Inspection of the problem (within the range of densities encountered in most rocks) using the PELSHIE program shows no change in radiation dose with density and thus the above two factors are probably fully self-compensating.

## 5.1.2 PRESENCE OF THORIUM OR POTASSIUM

In view of the extremely low gamma-activity of potassium and its relatively low concentration (mostly less than 5%) in nature, it may be considered to have a negligible effect on uranium or thorium ore grade determinations.

Thorium, which has a specific gamma-yield of roughly two-fifths that of uranium, does, however, pose a problem for most borehole logging units equipped only with a total-count facility. The effect of thorium can be corrected for only if the uranium/thorium ratio remains largely constant. This would have to be established by laboratory analyses on numerous samples over a wide concentration range.

## 5.1.3 DISEQUILIBRIUM

This is undoubtedly one of the chief sources of inaccuracy with *in situ* radiometric assaying and cannot readily be detected in the field with standard radiometric exploration instruments. Beta-gamma analysing systems, which overcome this problem, are available but are really applicable only to homogenised powdered material. The only firm guide which can be put forward to the field geologist is that where the uraniferous ore layer is situated well below the water table (i.e. below the zone of seasonal fluctuation) the ore can be expected to be in equilibrium (Corner, 1976; Corner and de Beer, 1976). Disequilibrium can also be expected to be a minimum in a fresh and unfractured outcrop showing little oxidation of the iron minerals. If, however, the degree of disequilibrium is a constant for an occurrence, as is often the case in arid areas, it can be corrected for by conducting an orientation study on a specific occurrence (Corner, 1976). This would involve a comparison, using linear-regression analysis, of numerous gamma-log grade determinations with chemical analyses of the corresponding borehole core or chip material. *In situ* radiometric-grade determinations on occurrences showing variable disequilibrium are of little value in ore-reserve estimations.

## 5.1.4 INSTRUMENT DEAD-TIME

Instrument dead-time, or the time it takes for an instrument to sample one pulse during which it cannot sample any other incoming pulses, may be a source of error, especially with high-grade ores (i.e. with high gamma-flux). This causes a deviation in linearity of an instrument resulting in pessimistic grade predictions. Most modern radiometric instruments have inherently low dead-times (less than 4  $\mu$ s) and do not require correction except for very high-grade ores. Some instruments also compensate electronically for this effect. A simple dead-time correction can be applied (Dodd and Eschliman, 1972) to the observed count rate as follows:

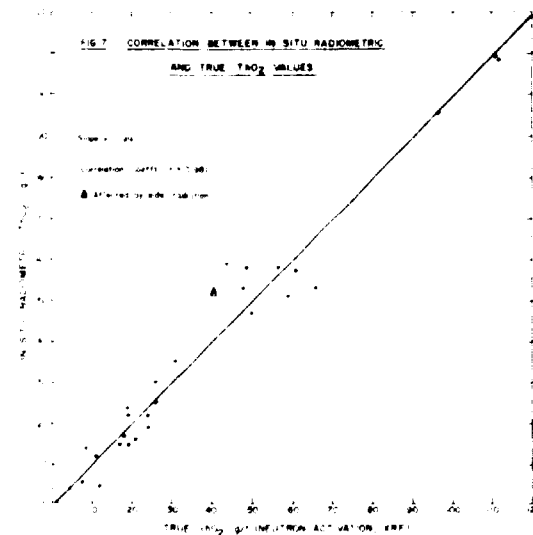
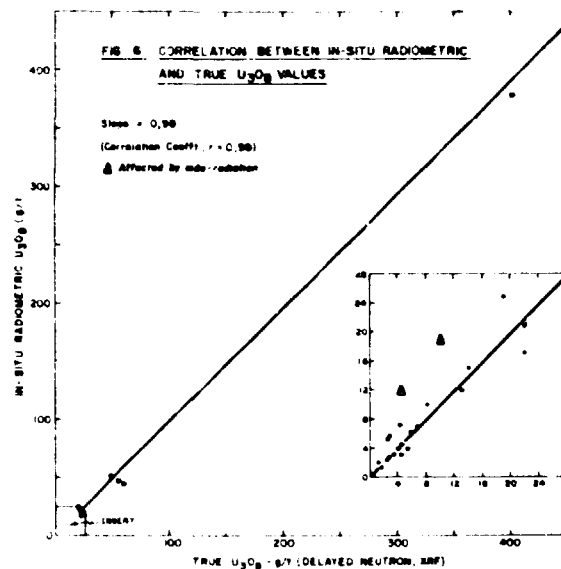
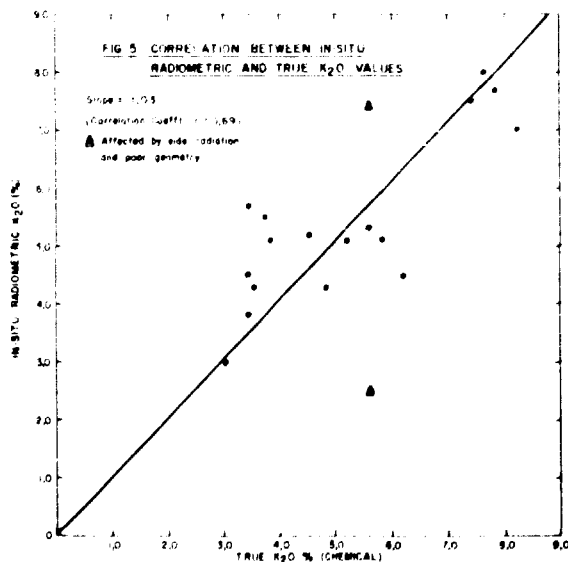
If  $n$  is the observed count rate  
 $N$  is the true count rate  
 and  $t$  is the instrument dead-time  
 then

$$N = \frac{n}{1 - nt}$$

Portable sources have been built at Pelindaba to enable the calculation of instrument dead-time, although analytical problems in determining their exact concentrations still remain to be solved.

### 5.2 Results of *In Situ* Radiometric Assays

In order to check the accuracy of *in situ* radiometric assaying, using the Pelindaba derived calibration constants, a number of selected outcrops were read with a calibrated spectrometer. Shallow boreholes of up to 150 mm were drilled into the fresh rock at each site and the cores were milled, homogenised and assayed at the Atomic Energy Board and Geological Survey for  $K_2O$ ,  $U_3O_8$  and  $ThO_2$ . The results, presented together with the field radiometric values in Table A1 in Appendix V, are plotted in Figs. 5, 6 and 7. The lines of best fit were calculated by the least squares method and show the radiometric values to be too high on average by a factor of 3% for potassium and too low by factors of 2% and less than 1% for uranium and thorium respectively - all well within the limits of experimental error. Overall linear correlation (as indicated by the correlation coefficients) is exceedingly good for the  $U_3O_8$  and  $ThO_2$  values and reasonable for the  $K_2O$  values. The reason for the large scatter and relatively low value of  $r$  (0,69) for the potassium data is felt to be chiefly due to inadequate counting statistics in view of the low gamma activities involved. Count rates used in the calculation of the radiometric concentrations were derived from four to five readings of 300 s each for the Geological Survey values (see Table A1) and four to five readings of 60 s each for the Atomic Energy Board values.



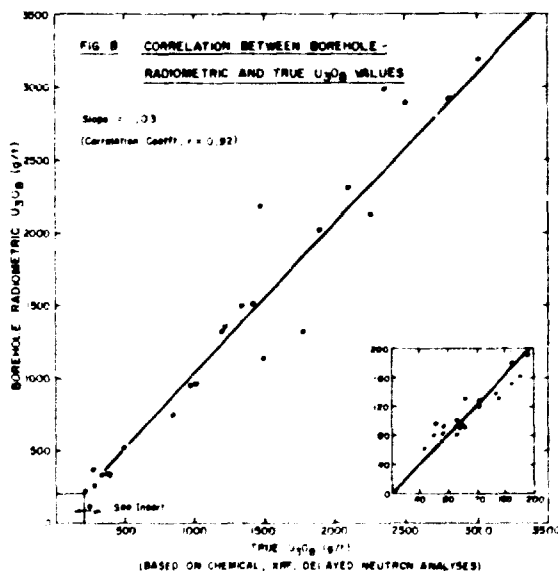
The scatter of the data could also arise from one or more of the following factors; inhomogeneity of the rocks sampled, inaccuracies in the laboratory determinations, inherent experimental error with the radiometric values and poor geometry (data points affected by side radiation are indicated as such in Figs. 5, 6 and 7).

Although sufficient data points are lacking in certain concentration ranges in the above Figures, it is felt that the data nevertheless indicate that *in situ* radiometric assaying is accurate provided the limiting factors discussed above are borne in mind. The linear correlations observed for uranium and thorium are anticipated to extend into the higher concentration ranges (not sampled in this exercise) in view of the fact that the calibration constants were derived from sources of high concentration. Errors in potassium determinations are, however, expected to increase, with increasing concentrations of uranium and thorium, due to the larger contributions of Compton scattered gamma rays in the potassium channel and hence a reduction in the signal-to-noise ratio.



The borehole results, presented in Fig. 8 are equally gratifying. They were derived from all mineralised holes logged to date by the Atomic Energy Board in at least seven different occurrences (sedimentary and granitic) throughout Southern Africa. Only intersections (50 in total) which were situated well below the water table (i.e. largely in equilibrium) and which were seen, through spectrometric checks on the anomalies, to contain little or no thorium, were chosen. Laboratory assays were provided by the contributing mining companies and were derived using XRF and chemical analyses on core or percussion-chip samples. Ore-layer thicknesses were normalised for each point, according to the intervals sampled, in order to make the laboratory- and radiometric-grade values directly comparable.

Linear regression of the data points in Fig. 8 shows the radiometric data to be optimistic by a factor of 3% with a high correlation coefficient of 0,92. Scatter of the above data is felt to be due chiefly to ore inhomogeneity (inevitably), methods of sampling the drilled material, laboratory inaccuracies and inherent experimental error.



A constant source of error could be the absolute concentration quoted for the uranium standard. In particular, no cognisance is taken, with gross-count logging, of the small amount of thorium in this standard. Considering the gamma activity of thorium in relation to uranium, the concentration of thorium in the borehole uranium source (134 g/t ThO<sub>2</sub>) is equivalent to roughly 53 g/t U<sub>3</sub>O<sub>8</sub> or 3,5% of the total equivalent uranium concentration. This is small considering the relatively large standard deviation associated with the actual uranium concentration of the source (1 440 ± 236 g/t U<sub>3</sub>O<sub>8</sub>). Numerous orientation surveys conducted by the AEB and exploration companies (of which Fig. 8 is an example), have shown that this concentration, without correction for the thorium in the source, generally yields U<sub>3</sub>O<sub>8</sub> grades to within 10% and mostly better than 5% of the true values.

Until more logging data become available (when the uranium concentration will be reviewed and modified if necessary) users are recommended to adopt the quoted uranium concentration as an absolute value for the standard.

Certain exploration groups have reported that K factors derived for instruments calibrated at the Grand Junction Facility in Colorado are higher than the Pelindaba equivalent by between 15 and 20%. The reason for this large discrepancy is being investigated. It can, however, be said that all the logging conducted by the AEB (results contained in confidential reports) in Southern Africa to date has never revealed overall discrepancies of this order unless the occurrence was known to be out of equilibrium, but has rather yielded accuracies, after regression analysis, mostly within 5% of the true grades. It is possible that the Grand Junction calibration sources have a higher radon loss than the Pelindaba sources, thus yielding relatively optimistic K factors.

## 6. CONCLUSIONS

The standard surface and borehole uranium, thorium and potassium sources at Pelindaba provide threefold benefits to the uranium exploration fraternity, viz.:

- (i) Provided cognisance is taken of the inherent limitations of gamma spectrometry, i.e. chiefly as regards the problems of disequilibrium, counting statistics and field geometry, observed count rates may be related quantitatively to the *in situ* equivalent or true uranium, thorium and potassium concentrations. Orientation studies with surface spectrometers and borehole loggers have shown that the radio-element concentrations may be predicted radiometrically with an accuracy of better than 5% over a range in concentration from less than 10 g/t U<sub>3</sub>O<sub>8</sub> or ThO<sub>2</sub> up to prevailing ore grades.
- (ii) Although instrument sensitivities may differ widely, uniformity can be obtained if scintillometer responses are expressed in terms of a standard unit of radio-element concentration, i.e. eU<sub>3</sub>O<sub>8</sub> as derived at the facility. The concept of eU<sub>3</sub>O<sub>8</sub> is thus far more meaningful to a field geologist than an arbitrary count rate and surveys with different instruments may be readily compared.
- (iii) The standard sources at Pelindaba also provide a reference for checking the correct functioning of instruments.

The calibration facility (which may be regarded as an integral part of any uranium-exploration program) will be extended to include additional borehole sources enabling supplementary calibration constants as well as diameter corrections and instrument dead-time values to be determined.

**ACKNOWLEDGEMENTS**

The assistance received from the West Rand Consolidated Mines, New Wellington of Africa Ltd and the Phalaborwa Mining Company who donated the ore material used for the sources, as well as the analyses conducted by the National Institute for Metallurgy, General Mining and Finance Corporation, Rio Tinto Zinc Corp., and the Chemistry and Isotopes and Radiation Divisions of the Atomic Energy Board, is gratefully acknowledged. The suggestions of and useful discussions held with numerous members of the mining industry are also greatly appreciated.

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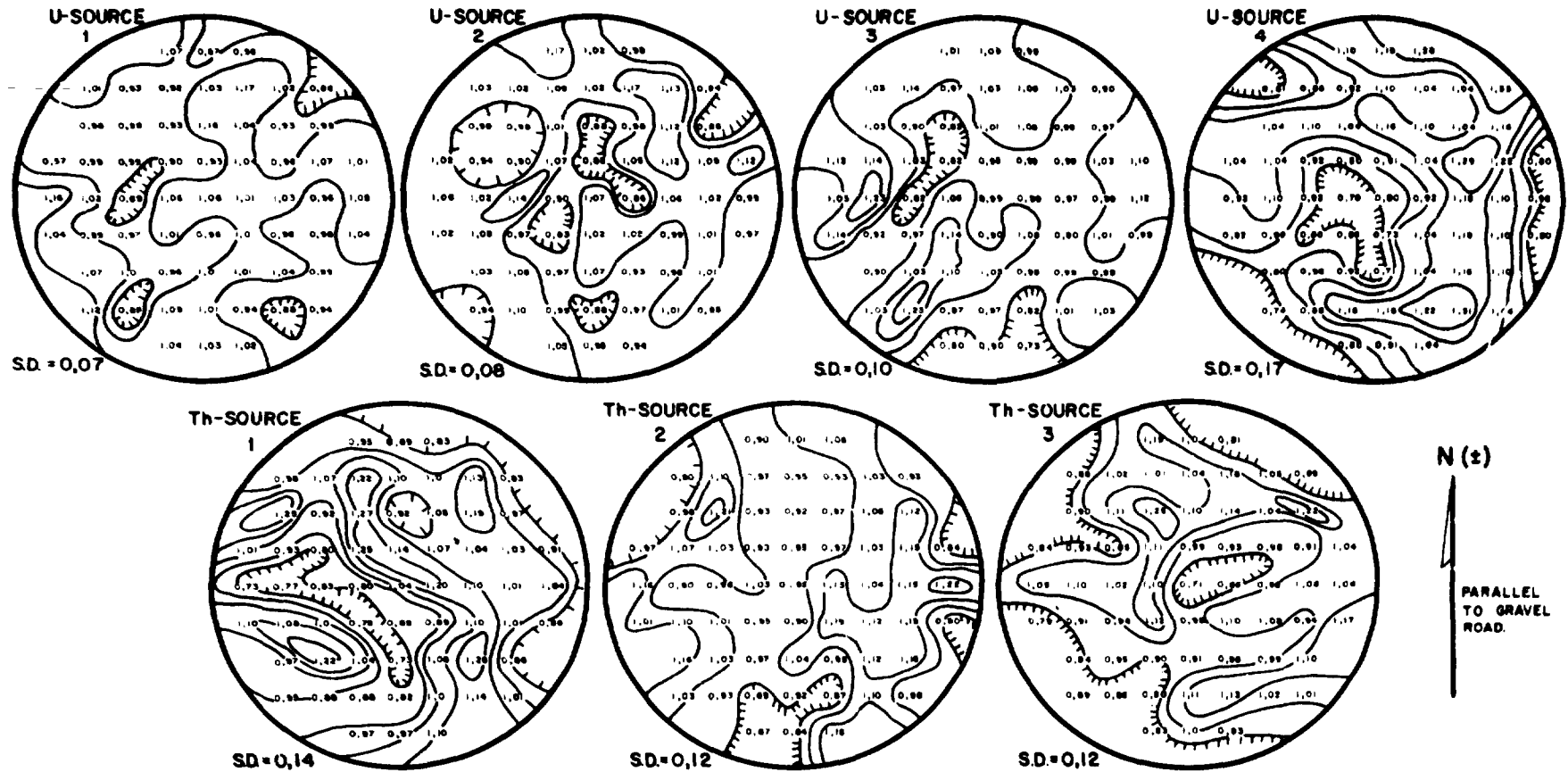
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APPENDIX I

PEL-268-18

**FIGURE A1 HOMOGENEITY OF THE STANDARD URANIUM AND THORIUM SOURCES**



**NOTE:** Values, contours and standard deviations (SD) were calculated using a lead-shielding technique and are normalised to an average of unity for each source

APPENDIX II

**CORRECTION OF THE TOTAL-COUNT-CHANNEL  $eU_{30g}$  RESPONSE FOR THE EFFECT OF THORIUM IN THE URANIUM SOURCES**

The procedure adopted for correcting for the effect of thorium in the uranium sources involves correction of the slope of the linear portion of the calibration curve rather than of each point individually. This is done since only a single calculation is necessary and any possible errors, due to poor counting statistics and analytical errors associated with the concentrations, are simultaneously reduced to a minimum.

The count rates measured on the uranium and thorium sources are functions of the concentrations of uranium, thorium and potassium in these sources. Since the concentration of potassium, which has a relatively low gamma-activity, is small in these sources, any effects due to its presence may, for practical purposes, be considered negligible. Thus

$$C_U = a_1 U_U + a_2 Th_U$$

and

$$C_{Th} = a_1 U_{Th} + a_2 Th_{Th}$$

where  $C_U$  and  $C_{Th}$  are the sums of the count rates (over the linear portion of the calibration curve) as measured on the uranium and thorium sources respectively;

$a_1$  and  $a_2$  are constants expressing the total-count channel response per unit concentration uranium and thorium respectively;

$U_U$  and  $Th_U$  are the respective sums of the uranium and thorium concentrations in the uranium sources corresponding to the count rates used in the calculation of  $C_U$ ;

and

$U_{Th}$  and  $Th_{Th}$  are the respective sums of the uranium and thorium concentrations in the thorium sources corresponding to the count rates used in the calculation of  $C_{Th}$ .

Solving the above equations for  $a_1$  and  $a_2$  we find

$$a_1 = \frac{Th_{Th} \cdot C_U - Th_U \cdot C_{Th}}{Th_{Th} \cdot U_U - Th_U \cdot U_{Th}}$$

and

$$a_2 = \frac{U_U \cdot C_{Th} - U_{Th} \cdot C_U}{U_U \cdot Th_{Th} - U_{Th} \cdot Th_U}$$

Thus for the field situation:

$$eU_{30g}(g/t) = \frac{1}{a_1} \times \text{Field count-rate (background corrected)}$$

where  $\frac{1}{a_1}$  is equivalent to the constant  $K_1$  in Section 4.1.1

The concentration components of  $a_1$  may be obtained from Table II in the text.

APPENDIX III

PEL 258 20

ATOMIC ENERGY BOARD  
 CALIBRATION DATA SHEET FOR GAMMA - RAY SCINTILLOMETERS AND SPECTROMETERS

<b>HEADING</b>		(Date, Instrument Model, Company, Observer, DO NOT exceed 80 characters)																									
<b>TOTAL - COUNT CALIBRATION</b>		<b>TYPE OF CALIBRATION</b> For Scintillometers or Total - count channel, indicate T For Spectrometer channels (K,U,Th) only, indicate S For Total count and Spectrometer channels, indicate B										T, S or B	<b>TOTAL - COUNT CALIBRATION</b>				Number of readings per height for U - Sources and Background Pad		1, 2 or 3	Number of readings per height for Th - Sources		0, 1, 2 or 3	<b>COUNTING TIME (SEC. UPS)</b>				
																							First four U - Sources and Th - Sources				
<b>TOTAL - COUNT CALIBRATION</b>		<b>U - SOURCES</b>	<b>SOURCE</b>	<b>U - 1</b>				<b>U - 2</b>				<b>U - 3</b>				<b>U - 4</b>				<b>U - 5</b>							
		<b>HEIGHT cm</b>	0	25	50	100	0	25	50	100	0	25	50	100	0	25	50	100	0								
		g/g U <sub>3</sub> O <sub>8</sub>	4400	3220	2350	1220	2460	810	1310	690	1490	1110	820	430	530	410	300	170	17								
		1 <sup>st</sup> Reading																									
		2 <sup>nd</sup> Reading																									
<b>TOTAL - COUNT CALIBRATION</b>		<b>Th - SOURCES</b>	<b>SOURCE</b>	<b>Th - 1</b>				<b>Th - 2</b>				<b>Th - 3</b>				<b>BACKGROUND PAD</b>											
		<b>HEIGHT cm</b>	0	25	50	100	0	25	50	100	0	25	50	100	0												
		g/g ThO <sub>2</sub>	14200	9700	6700	3450	4250	2900	2020	1030	3500	2410	1720	880	---												
		1 <sup>st</sup> Reading																									
		2 <sup>nd</sup> Reading																									
<b>SPECTROMETER CALIBRATION</b>		<b>NUMBER OF DIFFERENT HEIGHTS READ ABOVE THE U AND Th SOURCES</b>	NB If less than 4 heights read, omit readings at 100 cm, 50 cm and 25 cm in that order		<b>NUMBER OF READINGS PER HEIGHT FOR U AND Th SOURCES</b>	(maximum 5)		<b>NUMBER OF READINGS AT 0cm FOR POTASSIUM SOURCE AND BACKGROUND PAD</b>	(maximum 10)		<b>PLOTTING SCALE REQUIRED</b>	(ie A2, A3, A4 or A5)	<b>A</b>														
		<b>COUNTING TIME (seconds)</b>	U AND Th SOURCES		<b>COUNTING TIME (seconds)</b>	POTASSIUM SOURCE		<b>COUNTING TIME (seconds)</b>	BACKGROUND PAD																		
		<b>BACKGROUND READINGS</b>																									
		K - CHANNEL																									
		U - CHANNEL																									
Th - CHANNEL																											
<b>POTASSIUM SOURCE READINGS</b>																											
K - CHANNEL																											

NB With TOTAL - COUNT CALIBRATION all four heights should be read on the uranium sources. The thorium sources should be read if a correction of the eU<sub>3</sub>O<sub>8</sub> response curve, due to the thorium impurities in the uranium sources, is required. This correction will generally be less than 5%.

URANIUM SOURCES

SOURCE	CHANNEL	FIRST HEIGHT = 0 cm					SECOND HEIGHT = 25 cm				
1	K										
	U										
	Th										
2	K										
	U										
	Th										
3	K										
	U										
	Th										
4	K										
	U										
	Th										
SOURCE	CHANNEL	THIRD HEIGHT = 50 cm					FOURTH HEIGHT = 100 cm				
1	K										
	U										
	Th										
2	K										
	U										
	Th										
3	K										
	U										
	Th										
4	K										
	U										
	Th										

THORIUM SOURCES

SOURCE	CHANNEL	FIRST HEIGHT = 0 cm					SECOND HEIGHT = 25 cm				
1	K										
	U										
	Th										
2	K										
	U										
	Th										
3	K										
	U										
	Th										
SOURCE	CHANNEL	THIRD HEIGHT = 50 cm					FOURTH HEIGHT = 100 cm				
1	K										
	U										
	Th										
2	K										
	U										
	Th										
3	K										
	U										
	Th										

N.B. Any number of readings per channel up to 5 may be used, but this must be consistent for both the Uranium and Thorium sources. If less than five readings are taken they should be entered from left to right starting with the first column. The mixed and 5th Uranium sources are not used in the derivation of the calibration chart - they may be used to check the accuracy of the calibration constants.

APPENDIX IV

PEL 268 22

ATOMIC ENERGY BOARD

CALIBRATION DATA SHEET FOR RADIOMETRIC BOREHOLE INSTRUMENTS

HEADING (Company, Observer /s, Date)																								
INSTRUMENT DESCRIPTION (Make, model, serial No., probe No., crystal size etc.)																	K FACTOR: ** (Indicate shielding medium in borehole for data on this sheet)		= K		AIR WATER CASING & WATER (Delete whichever inapplicable)			
TYPE OF CALIBRATION	If Total-count calibration only, indicate T If Spectrometer calibration only, indicate S If Total-count and Spectrometer calibration, indicate B										T, S or B		If Total-count calibration in U-Source only, indicate TU If Total-count calibration in Th-Source only, indicate TT If Total-count calibration in both sources, indicate TB				TU, TT or TB		COUNTING TIME (Seconds)	Total-Count	U & Th Channels	Background		
U - B.H. SOURCE 1	Depth (cm)	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	Background	
	Total-count																							
	U-Channel																							
	Th-Channel																							
Th-B.H. SOURCE 1	Depth (cm)	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	Background	
	Total-count																							
	U-Channel																							
	Th-Channel																							

\* Background counts may be determined in Ongeluk lava at depths greater than 2.5 m in each hole  
 \*\* Use a separate data sheet for each shielding medium - HEADING and INSTRUMENT information only necessary for first data sheet

SOURCE	Ore layer thickness (cm)	U <sub>3</sub> O <sub>8</sub> (g/l)	ThO <sub>2</sub> (g/l)	Hole diameter (cm)
U Borehole Source 1	86	1440	134	11,0
Th Borehole Source 1	90	22	1104	11,5

APPENDIX V

TABLE A1  
COMPARISON OF *IN SITU*  
RADIOMETRIC AND LABORATORY ASSAYS

SAMPLE	K <sub>2</sub> O (%)		U <sub>3</sub> O <sub>8</sub> (g/t)		ThO <sub>2</sub> (g/t)	
	LAB.	RADIOMETRIC	LAB.	RADIOMETRIC	LAB.	RADIOMETRIC
*KW1	—	5,8	22	17	44	59
VR1	—	4,8	22	21	66	53
TS1	—	6,9	19	25	59	51
TS2	—	5,0	13	12	48	53
TS3	—	4,9	14	15	61	57
G21	—	5,3	14	15	31	35
KD1	—	4,8	55	47	112	108
KD2	—	5,0	61	45	111	109
**01	7,4	7,5	49	51	7,2	5,7
02	5,6	2,5	4,6	12	19	22
03	3,0	3,0	10,5	19	41	52
04	3,4	3,8	3,5	3,0	57	58
07	5,8	5,1	8,0	10	17	15
08	5,6	5,3	3,2	5,1	8,4	14
10	7,8	7,7	400	380	50	47
11	3,4	4,5	5,8	6,3	19	24
12	8,2	7,0	1,2	2,0	11	12
14	5,2	5,1	6,7	7,0	18	17
15	6,2	4,5	4,3	6,6	24	19
16	3,7	5,5	3,1	3,0	21	16
19	5,6	7,4	2,6	5,3	4	4
21	3,5	4,3	2,5	2,3	12	5
22	2,7	—	4,6	4,7	24	22
23	4,8	4,3	5,5	4,0	19	15
27	7,6	8,0	4,1	4,2	49	58
29	3,8	5,1	1,7	1,4	26	25
30	3,4	5,7	4,4	3,2	25	30
31	4,5	5,2	2,8	5,5	97	95
Correlation Coeff. (r)	0,69 (fair)		0,998 (high)		0,98 (high)	

\*Samples derived from the Bushveld Igneous Complex

This set of results comprises averaged radiometric values derived from Geological Survey report GH-2471 (Richards, 1978).

\*\*Samples derived from rocks of the Damara Mobile Belt

This set of laboratory values was derived at the AEB using delayed-neutron (U<sub>3</sub>O<sub>8</sub> values), neutron activation (ThO<sub>2</sub> values) and chemical (K<sub>2</sub>O values) techniques.

NOTE: Standard deviations that can be associated with the radiometric values are less than 10 % and mostly better than 5 %.





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