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ATOMIC ENERGY OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

A MATHEMATICAL EVALUATION OF INSTANT WORKING LEVEL METER METHODS

by

J.R. JOHNSON

Chalk River Nuclear Laboratories

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L'ENERGIE ATOMIQUE DU CANADA, LIMITEE

EVALUATION MATHEMATIQUE DES METHODES AYANT RECOURS AUX COMPTEURS INSTANTANES DE NIVEAUX DE TRAVAIL

par

J.R. Johnson

Résumé

On passe en revue quatre méthodes d'estimation des Niveaux de Travail ayant recours à des "compteurs instantanés de niveaux de travail". La précision de ces méthodes est évaluée pour la gamme de concentrations des descendants radioactifs à courte vie de ^{222}Rn que l'on trouve dans l'atmosphère des mines. On fait, également, une comparaison de l'incertitude générale du Niveau de Travail obtenu par ces méthodes et de celle du Niveau obtenu par la méthode de Kusnetz plus couramment employée.

L'Energie Atomique du Canada, Limitée
Laboratoires Nucléaires de Chalk River
Chalk River, Ontario
KOJ 1J0

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ABSTRACT

Four methods of estimating Working Levels with "Instant Working Level Meters" are reviewed. The accuracy and precision of these methods are evaluated for the range of concentrations of the short-lived daughters of ^{222}Rn that exist in mining atmospheres. Included is a comparison of the overall uncertainty in the Working Level as measured using these methods with that measured with the more commonly used Kusnetz method.

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TABLE OF CONTENTS

I. INTRODUCTION

Since the risk of miners developing lung cancer from breathing air contaminated by ^{222}Rn and its short-lived daughters (^{218}Po through ^{214}Po) was recognized (see St64 for a review) and the Working Level (WL) exposure was proposed as a measure of this risk (see Ho69 for a review), the need for a quick, simple and accurate method of measuring the WL of a mining atmosphere has existed. This need was partially met by the development of the Kusnetz method (Ku56) and its modifications, which is a slow, simple, and relatively accurate method (see ICRP77 for a review). More recently, various techniques for rapid WL measurements have been proposed (Gr73, Gr76, Hi75, Ja73, Mi76, Ro69, Ro72a, Sc76, Sh76, Sh77) and instruments, called Instant Working Level Meters (IWLM), have been developed to exploit these techniques (Gr76, Ja73, Mi76, Sc76, Sh76, Sh77 and Wa77).

These methods are all similar in that they (as does the Kusnetz method) require that a known volume of air be drawn through a filter in a known time, and that the radon daughter activity on the filter be measured during or after sampling; hence estimates of the concentration of activities in the air can be obtained. The methods described in this report, identified here for convenience as J-S (Ja73), MDA (Mi76, Sh76, Sh77), 3R-WL(Sc76) and Hill (Wa77) do not estimate the individual daughter activities, and thereby calculate the WL, as do others (Gr76, GC70). The techniques used by these four methods (and others of a like nature) rely on phenomenological relationships between measured activities on the filter at times during and/or after sampling and the WL. This report describes the results of an evaluation of the accuracy of these phenomenological methods for estimating WL values in air containing all reasonable ^{222}Rn daughter concentration ratios. Included for comparison is an evaluation of the modified Kusnetz method (ICRP77).

II. METHODS

A FORTRAN computer program was written to calculate the activity on a filter during and after sampling air containing ^{222}Rn and daughters. The essential characteristics of these daughters are listed in table 1. The input data required by the program are the assumed concentrations* of the daughters ^{218}Po (RaA), ^{214}Pb (RaB), and ^{214}Bi (RaC)(the concentration of the very short-lived ^{214}Po (RaC') is essentially equal to the RaC concentration), the air sampling rate and time, the counting time relative to the start of sampling, and the efficiency for counting each daughter. The output includes the average counts per minute for each of the daughters and the WL corresponding to the input daughter concentrations.

The equations that describe the buildup and decay of activities on the filter during and after sampling have been described in detail by other authors (see for instance Ev69). They are given in the Appendix for completeness.

The daughter concentrations considered to be reasonable are restricted by

$$R(t;\ C_B/C_A) \leq C_B/C_A \leq 1 \qquad (1)$$

$$R(t;\ C_C/C_A) \leq C_C/C_A \leq C_B/C_A \qquad (2)$$

where C_A, C_B and C_C are the concentrations of RaA, RaB and RaC respectively, and C_B/C_A and C_C/C_A are the ratio of concentrations that actually exist, which can have a range of values restricted by inequalities (1) and (2). These limits were also assumed by Rolle (Ro72b) and by James and Strong (Ja73).

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* *The term "concentration" should be taken as activity concentration throughout this report.*

$R(t;\ C_i/C_A)$ is the ratios of C_i to C_A at time t after the introduction of a pure ^{222}Rn source into a previously inactive volume of air. The curve calculated from these limits is shown as N in figure 1. The numbers on the curve are the growth time t, which is often called the "age" of the air.

The upper limit of equation 1 will obtain only if enough time has elapsed since pure ^{222}Rn was introduced into the volume of air so that secular equilibrium exists ($C_A = C_B = C_C$). The upper limit of equation 2 will obtain at secular equilibrium or if very "young" air ($C_B \simeq C_C \simeq 0$) is mixed with very "old" air ($C_A \simeq C_B \simeq C_C$). These upper limits form a continuum of points, shown as the line M in figure 1. The numbers on this curve are the values of $C_B/C_A = C_C/C_A$ multiplied by 100.

^{222}Rn daughter concentration ratios in mathematical models of ventilated mines (see for example Vo61) fall between the curves M and N of figure 1. Measured values in South African (Ro72b) and United States (Br69) mines also fall between these curves as was pointed out by James and Strong (Ja73). The points plotted in figure 1 were calculated from published data on radon daughters in modern uranium mines in the USA (Ge72, Ge77). The points outside the envelope formed by curves M and N are thought to result from inaccuracies in the measured concentrations, particularly those below the N side of the envelope. The points outside the envelope on the M side could result because the dynamic equilibrium of the daughter concentrations was disturbed by the measurement process*.

Concentrations of ^{222}Rn daughters corresponding to the upper and lower limits of equations 1 and 2 were used in the computer program with the appropriate sampling and measurement regimen of the techniques described in this report to construct envelopes for the allowed values

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* *The author wishes to thank P.G. Groer (ANL) for suggesting this possibility.*

of the relationships between measured activity and WL. These envelopes are displayed in the accompanying figures. The numbers on the N curves of these figures refer to the growth time, or age of air, and the numbers on the M curves are the values of $C_B/C_A = C_C/C_A$ multiplied by 100 as was the case for figure 1.

II-1 Hill Method

The Hill Method (Hi75) samples air for 2 minutes at 2 litres per minute, waits for one-half minute, counts total alpha for 2 minutes (A_o counts) waits 1 minute and counts total alpha for 2 minutes (A_1 counts). The ratio of A_1 to A_o is then used to obtain a working level factor (DP2M) from a supplied graph (dashed curve on figure 2, which is the one given in reference Hi75) or table and the XWL is calculated from

$$XWL = \frac{A_o}{DP2M} \times \frac{1}{\varepsilon} \qquad (3)$$

where ε is the average efficiency of the detector for RaA and RaC' alphas. (XWL is used here to designate the estimated working level, and TWL is used to designate the true working level, when there is a need to distinguish between the two.)

As an example, suppose $A_o = 550$, $A_1 = 400$ and $\varepsilon = 0.20$. Then the decay ratio is 0.73 and DP2M, from figure 2, is 3.3×10^3. The XWL estimate is therefore 0.83. The maximum and minimum TWL that correspond to curves N and M of figure 2 can be obtained from figure 3, which is a plot of XWL/TWL as a function of the decay ratio A_1/A_o. These are

$$0.76 \leqslant TWL \leqslant 0.92$$

II-2 J-S Method

The J-S method (Ja73) differs from Hill's in that the first alpha count is taken during sampling, and more than one sampling/counting regimen can be used. The procedure is to sample air at 10 litres per minute while counting alpha activity being collected on the filter (Activity = I_o) for 2, 5 or 10 minutes, wait 1 minute, and recount for the same length of time as that used for sampling (Activity = I_1). The ^{222}Rn daughter concentration ratios assumed by James and Strong (Ja73) to derive their WL relationships (dashed curves in figure 4) were those appropriate to a ventilated mine shaft with ^{222}Rn emanating from the walls along the shaft (Model C of reference Vo61). They use a detector efficiency ε=0.20 in these calculations.

As an example of the use of this method, suppose for a 5 minute sampling/counting periods, I_o = 5000 and I_1 = 6000, then I_1/WL = 1.45×10^4 (from figure 4) and

$$XWL = 6000/(1.45 \times 10^4) = 0.41$$

The maximum and minimum TWL can be obtained using the curves of figure 5, which are plots of XWL/TWL against the count ratio I_1/I_o for that correspond to curves M and N of figure 4. They are

$$0.34 \leqslant TWL \leqslant 0.43$$

II-3 MDA Method

This method employs an alpha and a beta counter and uses the sum of net alpha plus beta counts (the background of the counters are taken during sampling). This sum has been shown to be approximately proportional to the WL(Mi76) for the time after sampling that is used. The sampling/counting regimen is 2 minute sampling at 2.5 litres per minute, a one-half minute waiting time, and a one minute count (1st chance) or a four and a half minute waiting time and a one minute count (2nd chance). The detectors and geometries of this instrument have been selected so that one WL of 20 minute air (concentration ratios from curve N of figure 1 will result in 1000 net alpha plus beta counts for the 1st chance regimen (Sr77). The XWL is therefore obtained simply by shifting the decimal three places on the net counts. The 2nd chance regimen will give a net count reduced by approximately 1.3(Sh76). The XWL in this case is calculated from the net counts by

$$XWL = \text{net counts} \times 1.3 \times 10^{-3} \qquad (4)$$

Figures 6 and 7 give the envelopes of allowed values of TWL x C_A/100 as a function of net α plus β counts for the 1st and 2nd chance regimens respectively. If C_A is set equal to 100, the dashed lines on the figures represent the values of XWL calculated by the MDA method. [C_A is left in as a parameter on this graph, as it is for the 3R-WL and Kusnetz methods (below), to enable an estimate of the range of allowed values of the ratios XWL/TWL for these methods to be made (see figures 9, 10, 12 and 14).] It is evident that large errors can occur for "young" and "old" air, particularly for the 1st chance regimen. The recommended procedure of correcting for this error (Sh76, Sh77) is to assume the daughter activity is due to isolated ^{222}Rn decay (Curve N) and then calculate correction factors as a function of the net alpha to net beta count ratios, which is a measure of the age of the air (Sh76). These correction factors were calculated and plotted in figure 8.

Figures 9 and 10 give the maximum and minimum values for the ratio XWL/TWL as a function of TWL x C_A/100 for the 1st and 2nd chance regimens respectively, for both the corrected (using figure 8) and uncorrected values of XWL. A value of TWL x C_A/100 that can be used to estimate the range of XWL/TWL can be obtained from the ratio α/B of figure 8 and the numbers on the M and N curves of figures 8, 9 and 10.

II-4 3R-WL Method

The 3R-WL method (optimized, table 9 of reference Sc76) samples air at 2 litres per minute for 90 seconds, waits 10 seconds, and counts RaA and RaC' alphas separately (using a single detector and energy discrimination) for 100 seconds. It then uses the function

$$XWL = \frac{1}{200\varepsilon} (I_A/10 + I_{C'}) \tag{5}$$

where I_A and $I_{C'}$ are the counts from RaA and RaC' alphas respectively, and ε is the average efficiency for counting these alpha particles. Figure 11 gives the envelope of allowed values of the TWL x C_A/100.

II-5 Modified Kusnetz Method

The Modified Kusnetz method is identical to the Kusnetz method (Ku56) with a scaler replacing the rate meter. This method samples air for 5 or 10 minutes, waits for from 40-T/2 to 90-T/2 minutes, and counts for T minutes. The XWL is then calculated by dividing the average alpha disintegrations per minute per litre sampled (I) by a factor obtained from a graph (see figure 15).

For comparison with the above methods, a sampling time of 5 minutes, a waiting time to 38 minutes and a counting time of 4 minutes (5-38-4) was chosen. Figure 13 gives the envelope of allowed values using these conditions for WL x C_A/100 as a function of I. The dashed line, with C_A set equal to 100, gives XWL. Figure 14 gives the ratio XWL/TWL as a function of TWL x C_A/100.

The large error in the estimated working level of "young" air using the Kusnetz method has been noted before (Gr72). Rolle (Ro69, Ro72a) has suggested a method of improving the accuracy of the Kusnetz method while retaining the simplicity of a single alpha count. He noted that for short waiting periods, the fractional change of alpha activity with varying radon daughter concentration ratios became a minimum, and he worked out a method of selecting sampling, waiting, and counting times to minimize the error in the XWL. Figure 15 gives envelopes of allowed alpha activity as a function of waiting time for a 5 minute sampling time and a 4 minute counting time. The solid curves correspond to the maximum and minimum activity if the complete range of daughter concentration ratios given in figure 1 are used. The dashed curves correspond to maximum and minimum alpha activities if the range of concentration ratios are restricted to lie within an envelope formed by the M and N curves and lines joining (M,N) = (20,15) and (M,N) = (60,50) on figure 1. This envelope contains about eighty percent of the points plotted in figure 1. Figure 16 is a plot of the relative range of the alpha activity as a function of waiting time for these two envelopes. Note the local minimum at $T_w + 2 = 9$ minutes.

III. UNCERTAINTY IN WL ESTIMATES

III-1 Inaccurary

The inaccuracy in these methods of measuring WL caused by such things as air flow calibration, detector calibration and filter self-absorption are not considered here. Only considered are the inaccuracies introduced by the methods themselves. In an attempt to quantify these, two effects were considered. The first is the range of possible WL values corresponding to different daughter concentration ratios that would result in a particular measured value. The second is the bias in the WL estimates resulting from the choice of relationship between WL and the measured values. These two possible sources will be dealt with in turn.

III-1.1 Relative Range

The maximum ranges of WL that are consistent with given sets of measured activities are given by curves M and N on figures 3, 5 9, 10, 12, and 14 for the Hill, J-S, MDA 1st Chance, MDA 2nd Chance, 3R-WL and Kusnetz methods respectively. Table 2 lists the estimated relative range for three different nominal ages of air, where the relative range is taken to be

$$R = \frac{M-N}{(M+N)/2}$$

III-1.2 Relative Bias

The relative bias in the WL introduced by the phenomenological relationship was estimated from the difference between the WL estimates (dashed curves of figures 2, 4, 6, 7, 11 or 13; these dashed curves have been taken from, or calculated from, the references describing these different IWLM techniques) and the mid-point between curves M and N, divided by this midpoint value. The midpoint between curves M and N is not necessarily an unbiased estimate of the true WL; however, the points plotted on figure 1 indicate that it is very nearly so, at least for the mines represented by the points. These calculated relative biases are given in table 3 for three ages of air.

III-2 Imprecision

We are considering here only the method used and, therefore, the only contribution to the lack of precision in the results is the random nature of nuclear decay.

The number of counts detected in a given time is a binomial statistic (St66), which reduces to a Poisson statistic if the average decay rate over the counting period remains essentially unchanged. The advantage of approximating the binomial by the Poisson statistic is that the derivation of the variance of the measured counts is greatly simplified; it is the total counts. The criterion of a constant average decay rate is not satisfied for any of the methods considered here. However, the variance calculated by assuming that the measured counts is a Poisson statistic is the upper limit on the variance obtained if the binomial distribution were used (St66) and this approximation is used here. The percent standard deviation (P) in any of the measured counts, C, is therefore

$$P = 100/\sqrt{C}$$

These values are listed in table 4 for air containing 0.2 WL and the indicated ^{222}Rn daughter concentration ratios. Also listed are the uncertainties inherent in the Kusnetz method (see also Gr72 for estimates of the errors in this method). The calculation of the statistical error for the MDA, 3R-WL and Kusnetz methods was straightforward whereas the overall uncertainties for the Hill and J-S methods listed in table 4 were estimated as follows.

The imprecision of the Hill method due to the random nature of A_o and A_1 is (Be69)

$$\Delta WL = \left[\Delta DP2M^2 + \Delta A_o^2 - \frac{2\ \mathrm{Covar}\ (A_o, DP2M)}{A_o \times DP2M}\right]^{1/2}$$

where ΔWl, etc, are the percent standard deviations in the indicated quantities. The covar $(A_o, DP2M)$ is difficult to calculate and, therefore, the imprecision was estimated by

$$\Delta WL = \left[(\Delta DP2M - \Delta A_o)^2 + \Delta A_1^2\right]^{1/2}$$

This formula was derived by noting that an increase (decrease) in A_o results in an increase (decrease) in DP2M (see figure 2) which tends to leave the estimated working level unchanged. If these increases (decreases) exactly cancelled out, the DP2M would be proportional to $(A_1/A_o)^{-1}$ and ΔWL would be equal to ΔA_1. It can be seen by examining figure 2 and equation 3 that the increases (decreases) will not entirely cancel for all allowed ratios of A_1/A_o, and the additional variance in WL to be added to ΔA_1^2 has been taken to be $(\Delta DP2M-\Delta A_o)^2$, where ΔDP2M is estimated from figure 2 and ΔA_o.

As with the Hill method, the factor I_1/WL used in the J-S method is not independent of I_1. However, in this case, an increase in I_1 decreases the factor I_1/WL for the 2 and 5 minute sampling/counting regimens and both increases and decreases this factor for the 10 minute sampling/counting regimen, depending on the count ratio. An equation similar to the above equation, but with the sign of ΔI_1/WL and ΔI_1 included, was used to estimate the overall uncertainty associated with this method.

IV. SUMMARY

The evaluation of the methods described above indicates that there is very little reason to select one method over another if the uncertainty in the measured WL is the only criterion for selection. The exception is the 3R-WL method, which has a large range of WL's for the same measured values over the complete range of radon daughter concentration (see table 2 and figure 12). None of the methods, except the corrected MDA method, are very accurate for young air. Of particular interest is the bias in the Kusnetz method in this range of relative daughter concentrations (table 3 and figure 14) as this method is often used as a standard by which other methods are evaluated. This analysis demonstrates that for air with a nominal age less than approximately 10 minutes, a large bias in the measured working level is inevitable if the Kusnetz method is used.

Figure 1: The range of ^{222}Rn daughter activity concentration ratios for isolated ^{222}Rn growth (Curve N) and for mixtures of very young and old air (Curve M). The numbers on N represent the "age" of the air in minutes while those on M are the values of 100 x C_B/C_A and 100 x C_C/C_A. The points are from recent measurements in mines (Ge72, Ge77).

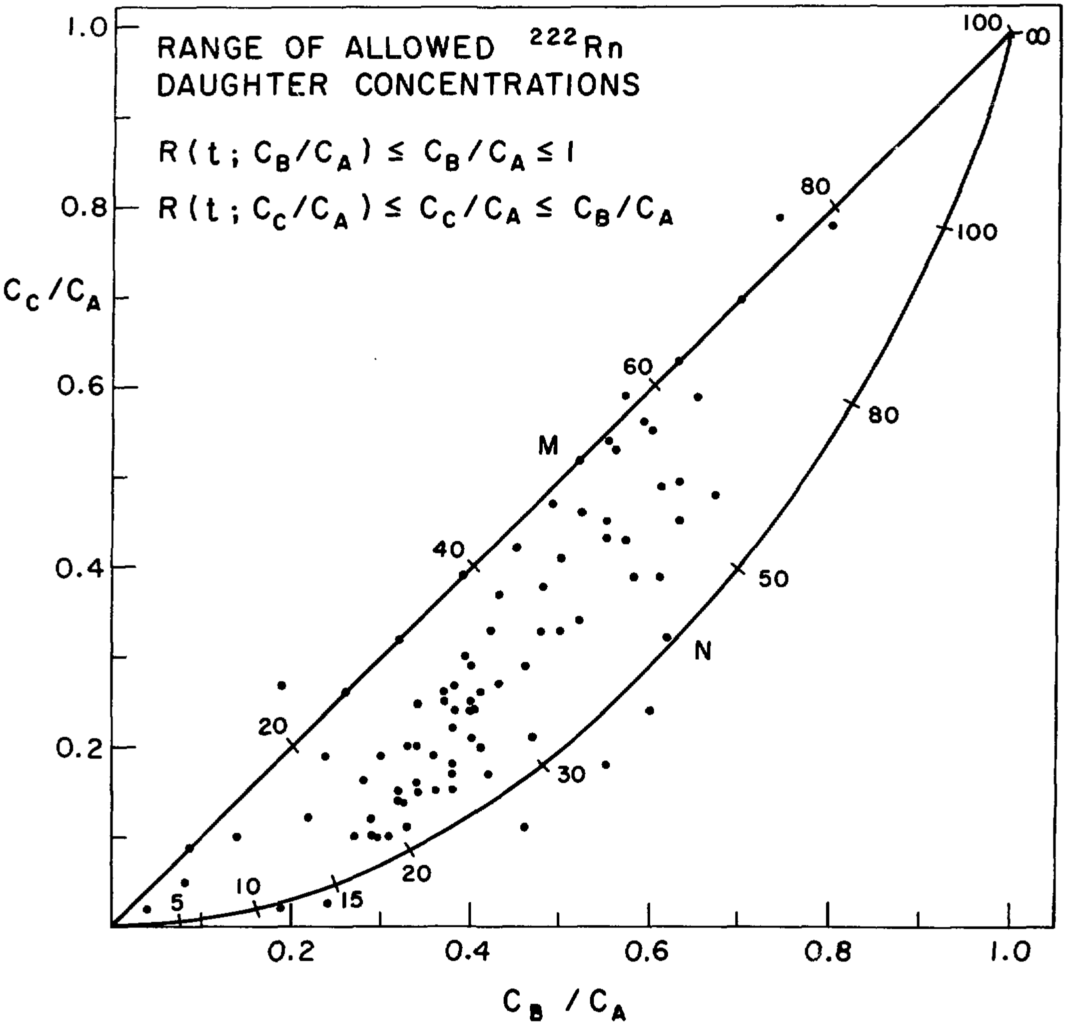

Figure 2: Phenomenological relationship (dashed curve) and envelope of values for the Hill method.

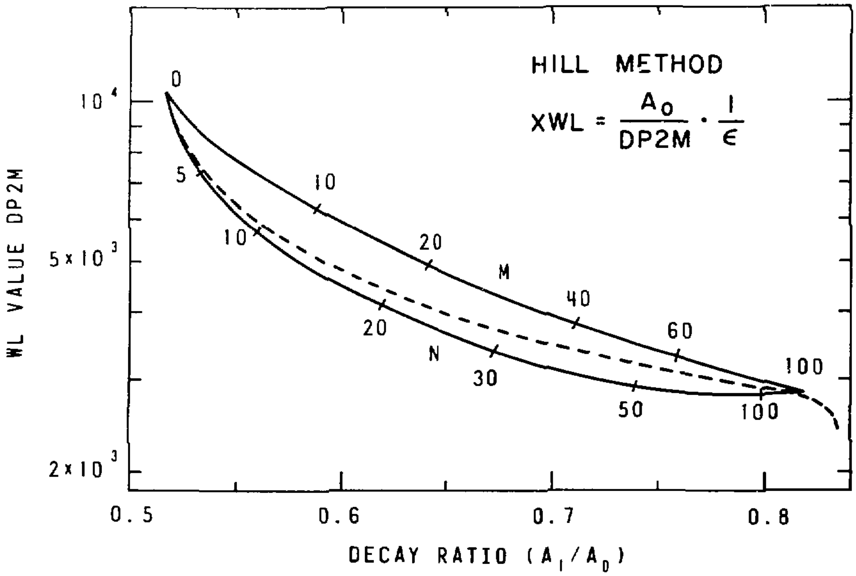

Figure 3: The range of allowed values of the measured working level (XWL) over the true working level (TWL) for the Hill method.

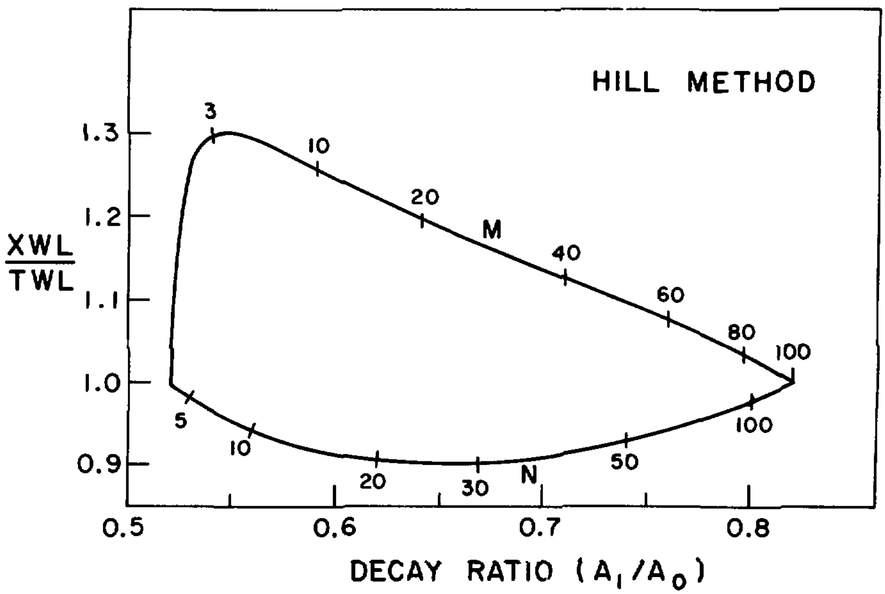

Figure 4: Phenomenological relationships (dashed curves) and envelopes of allowed values for the J-S method.

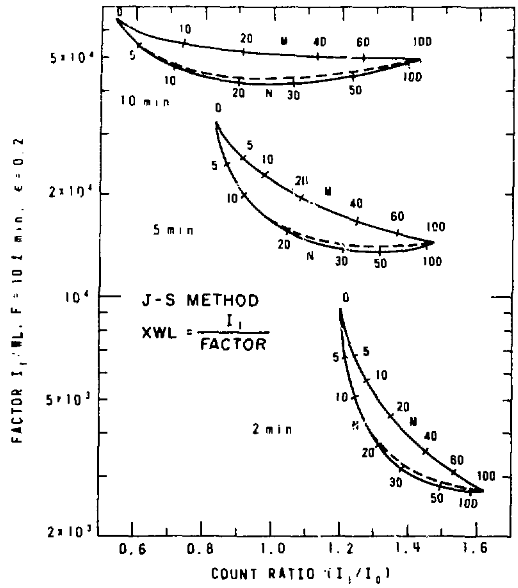

Figure 5: The range of allowed values of the measured working level (XWL) over the true working level (TWL) for the J-S method.

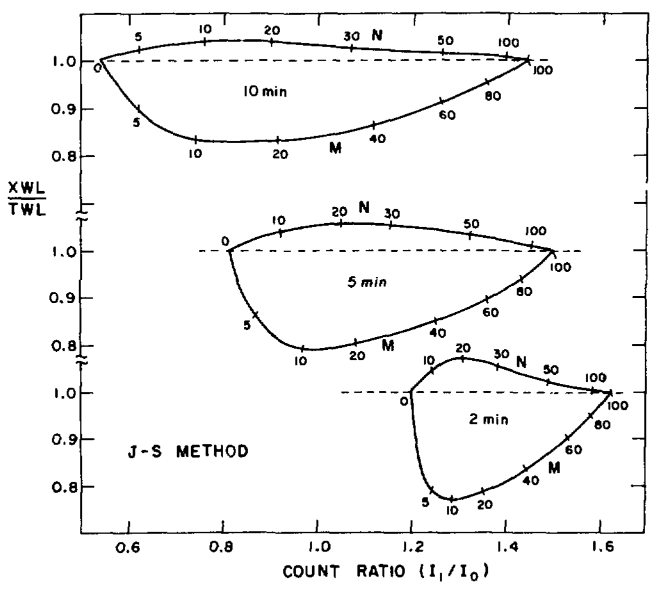

Figure 6: Phenomenological relationship (dashed line) and envelope of allowed values for the 1st Chance MDA method.

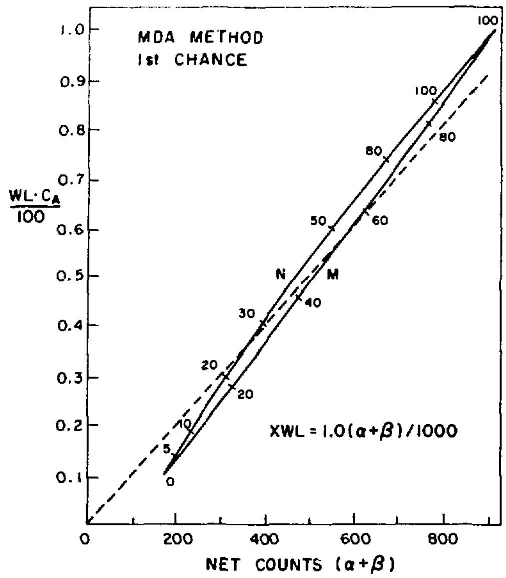

Figure 7: Phenomenological relationship (dashed line) and envelope of allowed values for the 2nd Chance MDA method.

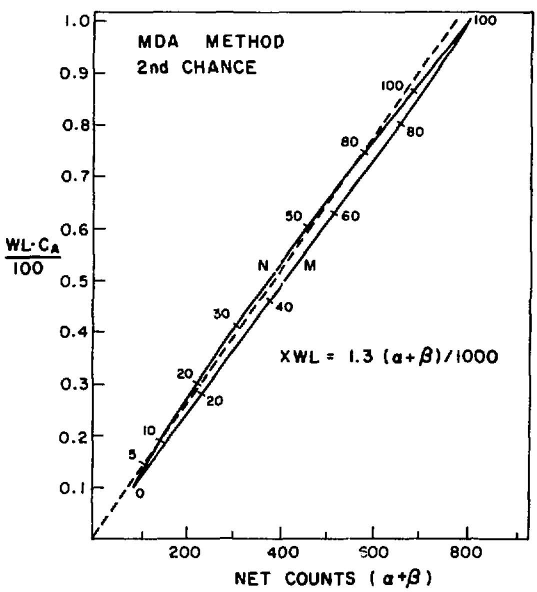

Figure 8: The correction factors used to correct the MDA methods.

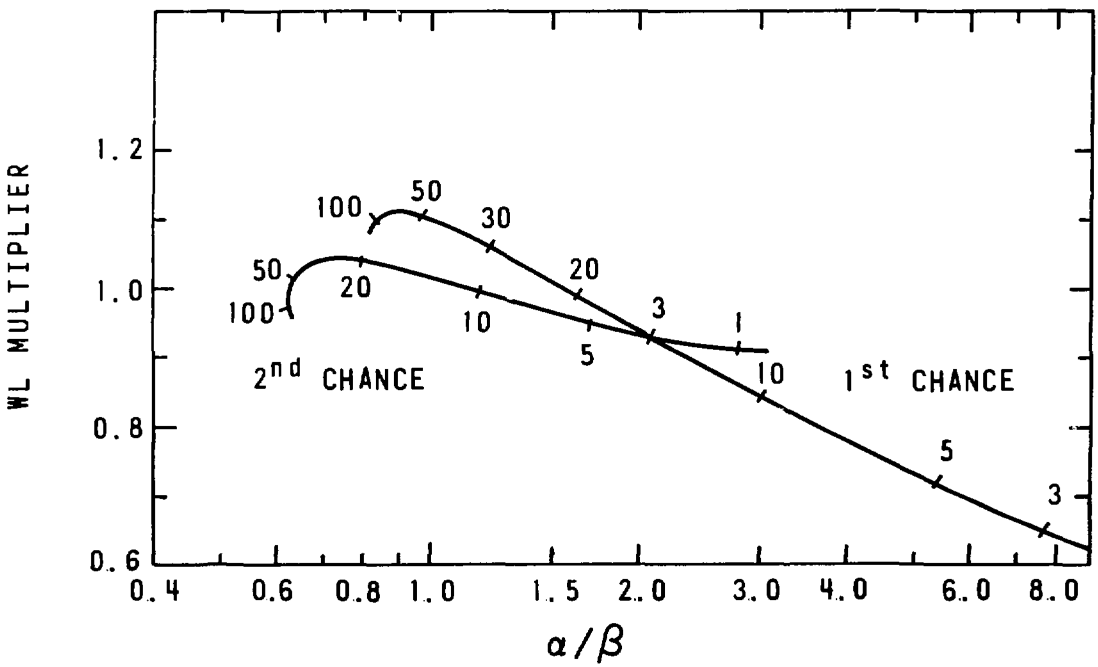

Figure 9: The range of allowed values of the measured working level (XWL) over the true working level (TWL) for the uncorrected and corrected 1st Chance MDA method.

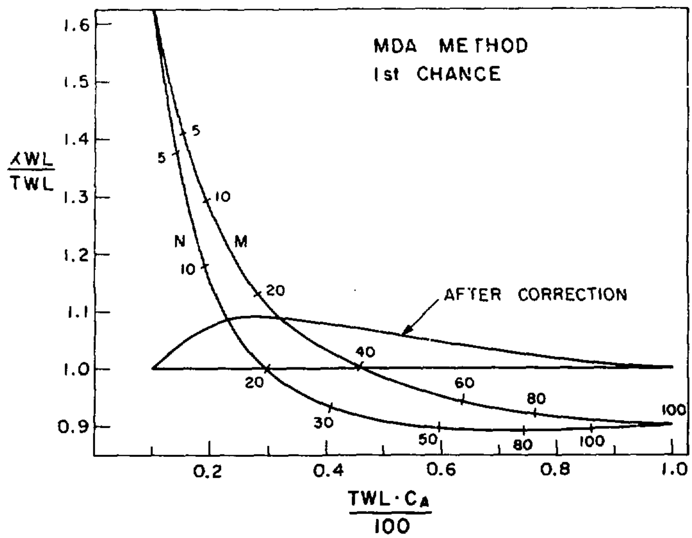

Figure 10: The range of allowed values of the measured working level (XWL) over the true working level (TWL) for the uncorrected and corrected 2nd Chance MDA Method.

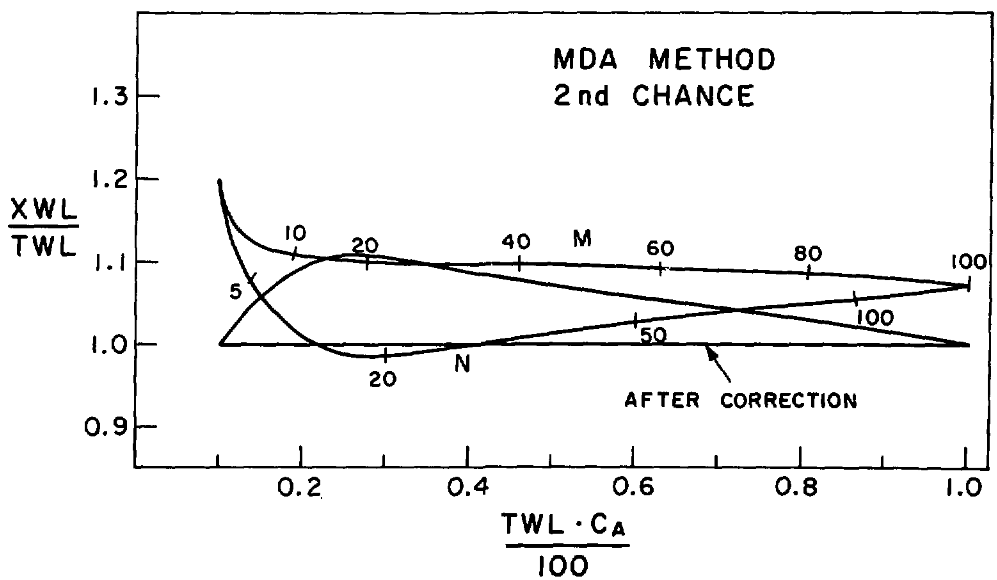

Figure 11: Phenomenological relationship (dashed line) and envelope of allowed values for the 3R-WL method.

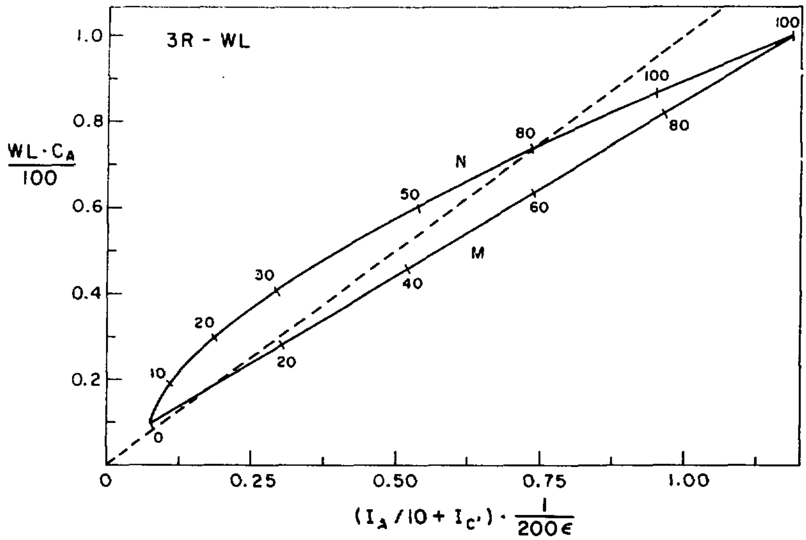

Figure 12: The range of allowed values of the measured working level (XWL) over the true working level (TWL) for the 3R-WL method.

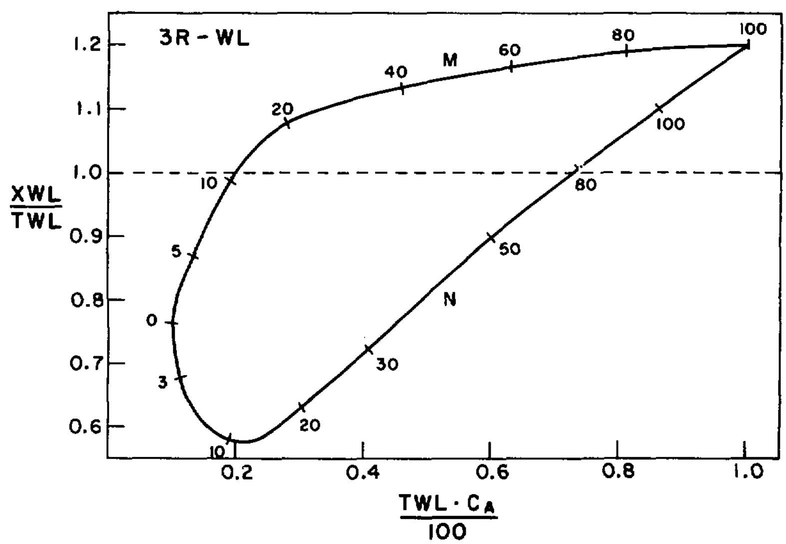

Figure 13: Phenomenological relationship (dashed line) and the envelope of allowed values for the Kusnetz method (5-38-4).

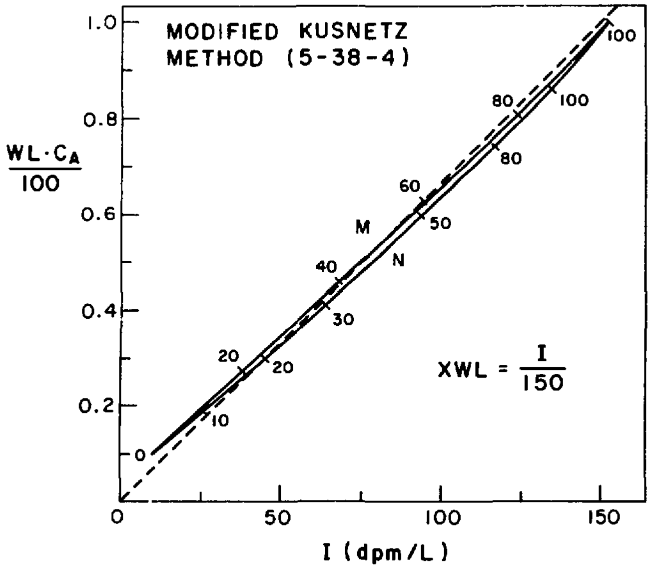

Figure 14: The range of allowed values of the measured working level (XWL) over the true working level (TWL) for the Kusnetz method (5-38-4).

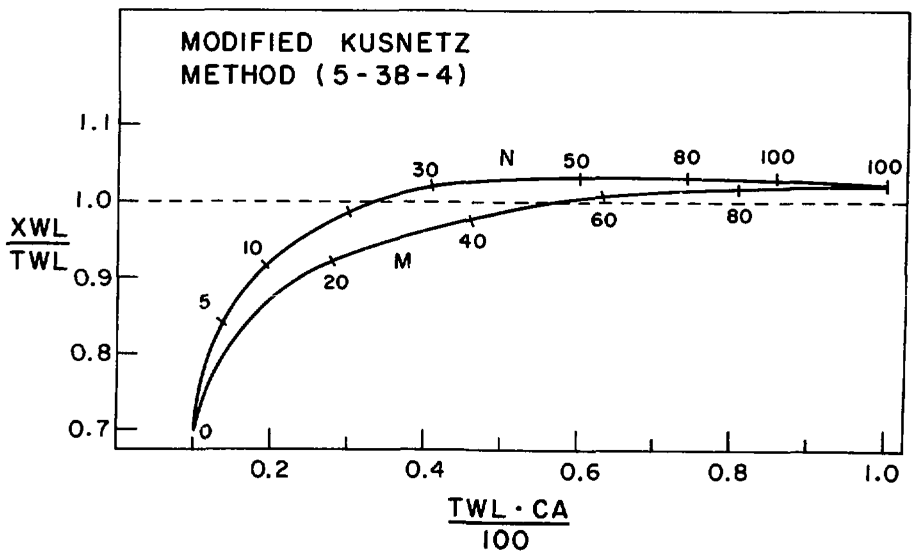

Figure 15: Range of allowed values for the alpha disintegration per minute per litre sampled per WL for a 5 minute sampling period and a 4 minute counting period as a function of waiting time (T_w).

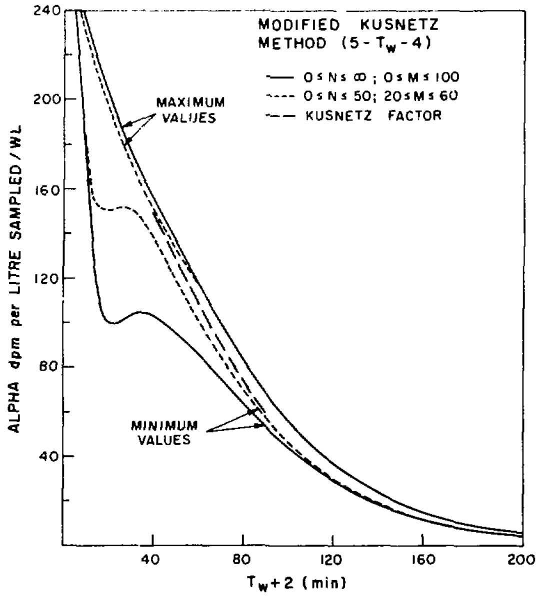

Figure 16: Relative range as a function of T_w corresponding to the maximum and minimum values given in figure 15.

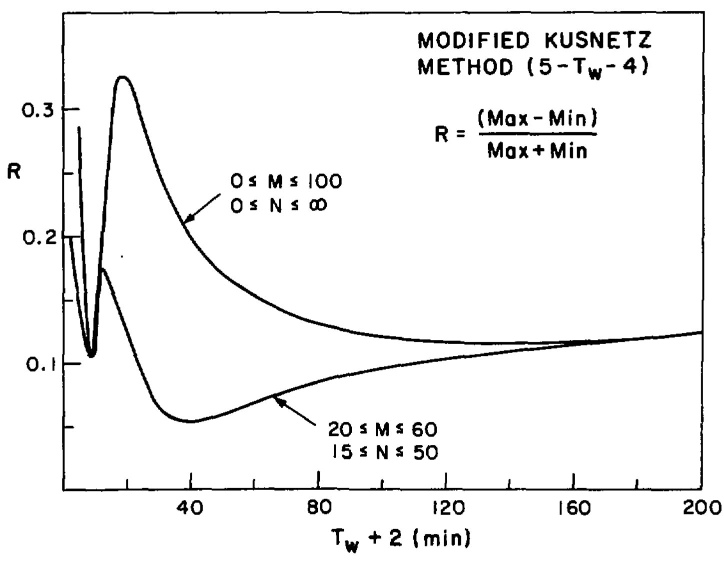

TABLE 1

Nuclide	Decay Mode	Half Life (min)	Alpha Energy (MeV)	Number of Atoms per 100 pCi*	Potential alpha energy per atom (MeV)	% Contribution to WL at equilibrium
^{218}Po(RaA)	α	3.05	6.00	977	13.68	10
^{214}Pb(RaB)	β	26.8	0	8380	7.68	52
^{214}Bi(RaC)	β	19.7	0	6310	7.68	38
^{214}Po(RaC')	α	$2.7\text{x}10^{-6}$	7.68	$8.7\text{x}10^{-4}$	7.68	0

WL = 1.3×10^{5} MeV potential alpha energy in one litre of air from the decay of the ^{222}Rn daughters ^{218}Po through ^{214}Po.

* Ci = 37 GBq

TABLE 2: Relative range (R) of possible WL estimated values for different ages of air. R = 2(M-N)/(M+N)

METHOD	Nominal Age of Air and Relative ^{222}Rn daughter concentrations (time(min) - C_A:C_B:C_C)		
	5-1.0:0.07:01	30-1.0:0.48:0.18	100-1.0:0.92:0.78
Hill	0.16	0.25	0.09
J-S (2 min)	0.21	0.27	0.04
J-S (5 min)	0.15	0.25	0.04
J-S (10 min)	0.11	0.18	0.03
MDA (1st chance)	0.07	0.13	0.01
MDA (2nd chance)	0.07	0.08	0.01
3R-WL	0.35	0.43	0.09
Kusnetz (5-38-4)	0.05	0.07	0.03

TABLE 3: Relative bias (B) in WL value. B = (M+N-2P)/(M+N)

METHOD	Nominal Age of Air and Relative ^{222}Rn daughter concentrations (time(min) - C_A:C_B:C_C)		
	5-1.0:0.07:0.01	30-1.0:0.48:0.18	100-1.0:0.92:0.78
Hill	- 0.08	- 0.04	0.0
J-S (2 min)	- 0.11	- 0.13	- 0.01
J-S (5 min)	- 0.08	- 0.12	- 0.01
J-S (10 min)	- 0.05	- 0.09	- 0.01
MDA* (1st chance)	+ 0.44	- 0.06	- 0.09
MDA* (2nd chance)	+ 0.05	- 0.04	+ 0.02
MDA (1st chance)	+ 0.04	+ 0.07	+ 0.01
MDA (2nd chance)	+ 0.04	+ 0.04	+ 0.01
3R-WL	- 0.35	- 0.09	+ 0.13
Kusnetz (5-38-4)	- 0.21	- 0.02	+ 0.03

* *Uncorrected values (see text)*

TABLE 4: Relative Precision[1)] of the the methods for ^{222}Rn daughter concentrations corresponding to 0.2 WL with the indicated relative concentrations

METHOD	Nominal Age of Air and Relative ^{222}Rn Daughter Concentrations (min - C_A:C_B:C_C)		
	5-1.0:0.07:0.01	30-1.0:0.48:0.18	100-1.0:0.92:0.78
Hill A_o	5.8	8.6	9.4
A_1/A_o	10	13	11
Overall[2)]	15	10	11
J-S (2 min) I_1	2.7	4.0	4.3
I_1/I	3.5	5.1	5.8
Overall[2)]	40	11	5
J-S (5 min) I_1	1.4	1.9	1.9
I_1/I_o	1.7	2.1	2.1
Overall[2)]	20	2	2
J-S (10 min) I_1	1.0	1.1	1.0
I_1/I_o	1.0	1.1	1.1
Overall[2)]	10	1	1
MDA (1st chance)	6.4	7.7	7.9
MDA (2nd chance)	8.4	8.7	0.84
3R-WL	9.4	16	15
Kusnetz[3)] (5-38-4)	7.1	6.4	6.3

1) As a percent standard deviation.

2) These errors include the error in the selecting the factor from the graphs caused by the random fluctuations of nuclear decay.

3) Sampling at 2 litres per min and with a counting efficiency of 0.20.

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APPENDIX

This appendix gives the necessary equations for calculating the disintegration rates of the short-lived daughters of ^{222}Rn on a filter during or after sampling air containing these daughters. The approach used to write the equations lends itself readily to putting the equations into a computer code.

Symbols Used

A_o, B_o, and C_o are the activity concentrations in air of RaA, RaB and RaC respectively (the activity of RaC' is always essentially equal to the activity of RaC because of its very short half-life). These concentrations are taken to be constant over the sampling period. Q_A^s, Q_B^s and Q_C^s are the activities of RaA, RaB and RaC respectively on the filter after sampling air at a rate V' for a time t_s. Q_A^w, Q_B^w and Q_C^w are the daughter activities on the filter at a time t_w from the end of sampling to the end of the waiting period. t_c is the counting period, usually beginning at the end of the waiting period, but sometimes beginning at the beginning of sampling. λ_A, λ_B and λ_C are the radioactive decay constants of the daughters.

The rate of buildup of radon daughter activity on the filter during sampling is

$$\frac{dQ_A(t)}{dt} = A_o V' e^{-\lambda_A t} \qquad \text{A-1}$$

$$\frac{dQ_B(t)}{dt} = B_o V' e^{-\lambda_B t} + A_o \lambda_B V' \left[\frac{e^{-\lambda_A t}}{\lambda_B - \lambda_A} + \frac{e^{-\lambda_B t}}{\lambda_A - \lambda_B}\right] \qquad \text{A-2}$$

$$\frac{dQ_C(t)}{dt} = C_o V' e^{-\lambda_C t} + B_o \lambda_C V' \left[\frac{e^{-\lambda_B t}}{\lambda_C - \lambda_B} + \frac{e^{-\lambda_C t}}{\lambda_B - \lambda_C}\right] +$$

$$A_o \lambda_B \lambda_C V' \left[\frac{e^{-\lambda_A t}}{(\lambda_B-\lambda_A)(\lambda_C-\lambda_A)} + \frac{e^{-\lambda_B t}}{(\lambda_A-\lambda_B)(\lambda_C-\lambda_B)} + \frac{e^{-\lambda_C t}}{(\lambda_A-\lambda_C)(\lambda_B-\lambda_C)} \right] \qquad \text{A-3}$$

The integrals of these equations from $t=0$ to $t=t_s$ are obtained by replacing

$$e^{-\lambda_i t} \text{ by } \frac{1-e^{-\lambda_i t_s}}{\lambda_i} \qquad \text{A-4}$$

for all the i's, and are the daughter activities (Q_i^s) on the filter at the end of sampling. As an example, the RaB activity on the filter is

$$Q_B^s = B_o V' \frac{1-e^{-\lambda_B t_s}}{\lambda_B} + A_o V' \lambda_B \left[\frac{1-e^{-\lambda_A t_s}}{\lambda_A(\lambda_B-\lambda_A)} + \frac{1-e^{-\lambda_B t_s}}{\lambda_B(\lambda_A-\lambda_B)} \right] \qquad \text{A-5}$$

The average disintegration rate for each daughter on the filter during sampling is numerically equal to

$$Q_i^s / t_s \qquad \text{A-6}$$

The activity on the filter at the end of the waiting period can be obtained from equations A-1 through A-3 with Q_A^s, Q_B^s, and Q_C^s replacing A_oV', B_oV' and C_oV' respectively, t_w replacing t, and the Q_i^w replacing $\frac{dQ_i}{dt}$. As an example

$$Q_B^w = Q_B^s \, e^{-\lambda_B t_w} + Q_A^s \lambda_B \left[\frac{e^{-\lambda_A t_w}}{\lambda_B-\lambda_A} + \frac{e^{-\lambda_B t_w}}{\lambda_A-\lambda_B} \right] \qquad \text{A-7}$$

with Q_B^s obtained from equation A-5 and

$$Q_A^s = \frac{A_o V'}{\lambda_A} (1 - e^{-\lambda_A t_s}) \qquad \text{A-8}$$

The average disintegration rate for each daughter during the counting time t_c is obtained by integrating equations A-1, A-2 and A-3, with Q_A^w, Q_B^w and Q_C^w replacing A_oV', B_oV' and C_oV' respectively, from t=0 to $t=t_w$ and dividing by t_w. As an example, the equation for the average disintegration rate of RaB, during a time t_c, after waiting a time t_w, following air sampling for a time t_s, is

$$D_B = \frac{1}{t_w}\left\{\frac{Q_B^w}{\lambda_B}(1 - e^{-\lambda_B t_c}) + Q_A^w\lambda_B\left[\frac{1 - e^{-\lambda_A t_c}}{\lambda_A(\lambda_B - \lambda_A)} + \frac{1 - e^{-\lambda_B t_c}}{\lambda_B(\lambda_A - \lambda_B)}\right]\right\} \qquad \text{A-9}$$

with Q_B^w given by equation A-7, and

$$Q_A^w = Q_A^s\, e^{-\lambda_A t_s} \qquad \text{A-10}$$

with Q_A^s from equation A-8.

The similarities in the form of equations A-2, A-5, A-7 and A-9, and of the required equations for RaA and RaC, reduce the amount of computer coding required to calculate the individual daughter disintegration rates.

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