Simple Real-Time Measurements of WL and WLM with an Alpha CAM through the Utilization of Fundamental Concepts (LA-UR-12-20298)

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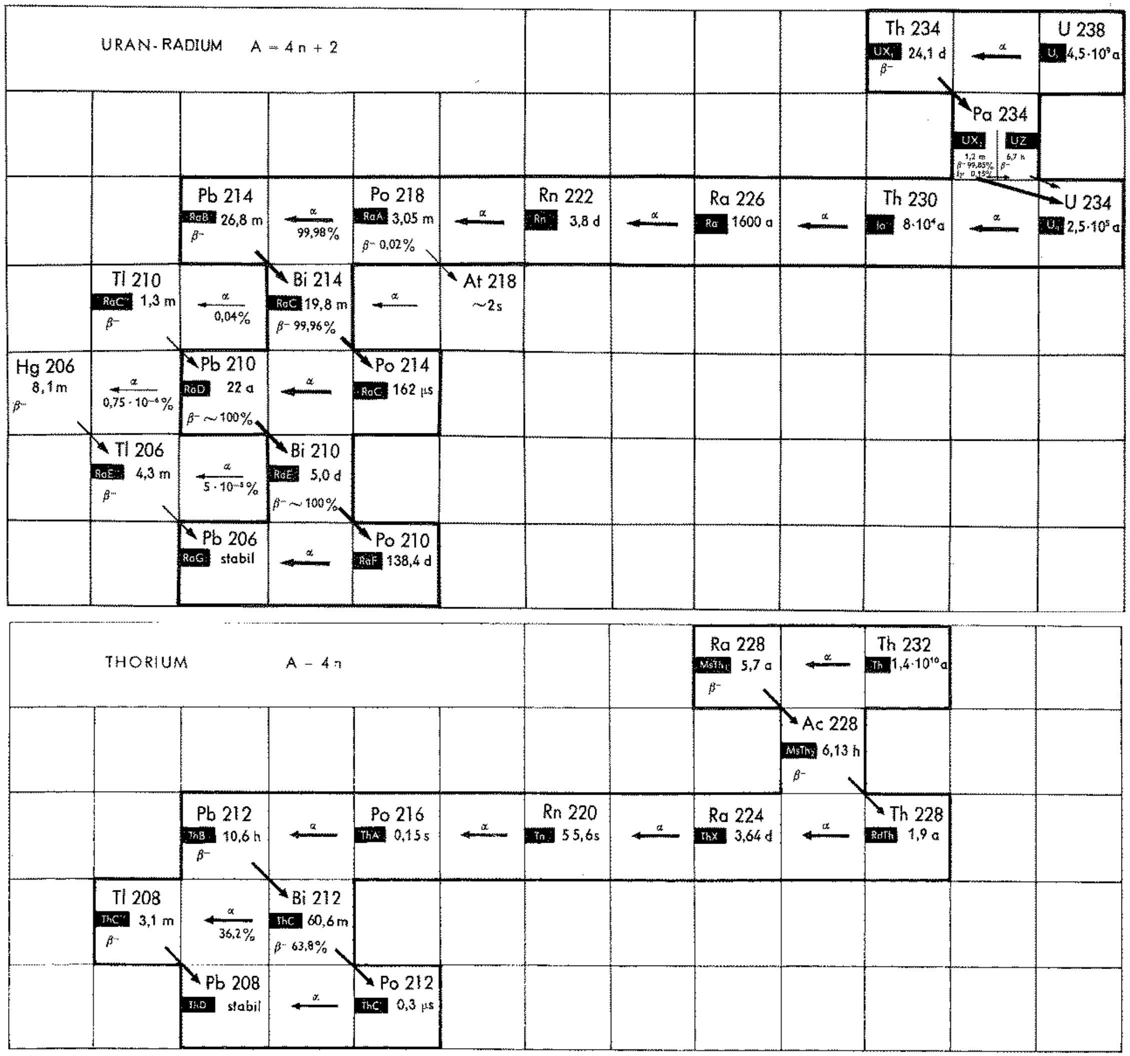
Abstract

Many working level (WL) measurements are based upon radon progeny concentration determinations using multiple timed counts or even multiple detectors. An alternative approach is presented that makes use of the fundamental definition of WL, with an alpha CAM conceptually replacing the role of a human lung. Simple algorithms are given for WL(Rn), WL(Tn), WL(total), as well as WLM(Rn) and WLM(Tn).

^{222}Rn and ^{220}Rn decay chains



Working Level (^{222}Rn, ^{220}Rn) Derivation

	Eff. α energy (MeV)	Half-life	# atoms per 100pCi,equil	Ultimate α energy	α energy per 100 pCi	%
^{222}Rn	5.49	3.824 d	$1.76x10^{6}$	na	na	na
^{218}Po (RaA)	6.00	3.098 m	$9.92x10^{2}$	6.00 + 7.69	$1.358x10^{4}$	10.57
^{214}Pb (RaB)	0	26.8 m	$8.58x10^{3}$	7.69	$6.597x10^{4}$	51.32
^{214}Bi (RaC)	0	19.9 m	$6.37x10^{3}$	7.69	$4.899x10^{4}$	38.11
^{214}Po (RaC′)	7.69	164 μs	$8.77x10^{-4}$	7.69	$6.741x10^{-3}$	$5.2x10^{-6}$
					$1.285x10^{5}$	100.0

Note: WL ≡ 1.3 x 10^{5} MeV/l and 101.1 pCi/l = 1 WL, or 1 pCi/l = 0.00989 WL

	α energy (MeV)	Half-life	# atoms per 100pCi,equil	Ultimate α energy	α energy per 100 pCi	%
^{220}Rn	6.28	55.6 s	$2.97x10^{2}$	na	na	na
^{216}Po (ThA)	6.78	0.145 s	$7.74x10^{-1}$	6.78 + 7.803	$1.129x10^{1}$	$6.5x10^{-4}$
^{212}Pb (ThB)	0	10.64 h	$2.04x10^{5}$	7.803	$1.595x10^{6}$	91.34
^{212}Bi (ThC)	<6.05>	60.55 m	$1.94x10^{4}$	7.803	$1.513x10^{5}$	8.663
^{212}Po (ThC′)	8.78	0.299 μs	$1.6x10^{-6}$	8.78	$1.402x10^{-5}$	$8.0x10^{-10}$
					$1.747x10^{6}$	100.0

Note: 7.44 pCi/l = 1 WL, or 1 pCi/l = 0.134 WL (i.e., 13.6 times that of Rn-222 progeny)

Working Level (^{222}Rn)

- **Many WL(Rn) measurements are based on concentration determinations using multiple timed counts and/or detectors. These standard methods use the following relationship between the radon WL and progeny concentrations:**

$$WL(Rn) \cong 0.01 \cdot \{ 0.106[RaA] + 0.513[RaB] + 0.381[RaC] \} \qquad (1)$$

where: [ ] denotes the progeny concentration in pCi/l.

- **A simple alternative approach makes use of the fundamental definition of working level: the deposition of $1.3x10^5$ MeV of potential alpha energy per liter of air. The point is that modified-Tsivoglou type or multiple detector methods for concentration determinations might not be necessary. The alpha CAM behaves as a person's lung and becomes a type of alpha dosimeter, even while equilibrium activities are being established as well as post sampling.**

Working Level (^{222}Rn) alone

- **First, a relationship that doesn't even require alpha spectrometry within the continuous air monitor (CAM), i.e., simply gross alpha, can readily be developed as follows:**
- **1) Assume that no RaA is present. We then have 7.69 MeV/alpha dis per $1.3x10^5$ MeV/WL-liter = $5.9x10^{-5}$ WL-l/alpha dis.**
- **2) Assume that only RaA is present. Then we expect 6.00+7.69 MeV per 2 alphas, or an average of about 6.84 MeV per alpha. Hence we then have 6.84 MeV/alpha dis per $1.3x10^5$ MeV/WL-liter = $5.3x10^{-5}$ WL-l/alpha dis.**
- **3) The average numeric factor for the more realistic cases between these extremes (i.e., all cases) could then be $5.6x10^{-5}$. This represents bias of +5.7% and -5.1% with respect to the $5.3x10^{-5}$ and $5.9x10^{-5}$ factors above, which is deemed quite acceptable within this field of measurement.**

Working Level (^{222}Rn) alone - cont.

- In other words, from a ***gross*** alpha CAM, WL(Rn) = $5.6 \times 10^{-5} \cdot$ alpha dis/liter, or

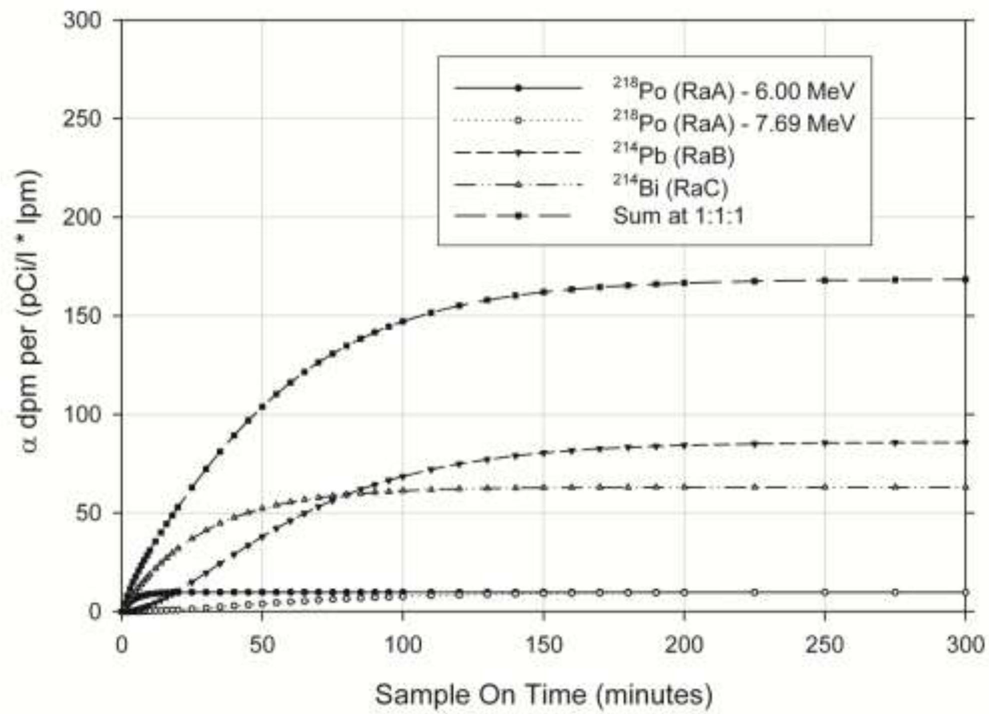
$$WL(^{222}Rn) = 5.6 \times 10^{-5} \cdot cpm_{\alpha} \;/\; [F(lpm) \cdot \varepsilon_{\alpha}] \qquad (2)$$

where:

- cpm_{α} is the ***gross*** alpha count rate from radon progeny,
- F is the air sampling flow rate in lpm, and
- ε_{α} is the alpha counting efficiency in counts per dis.

Working Level (^{222}Rn) alone - cont.

Example 1: **To test this relationship, it is known that at a 1:1:1 ratio (i.e., fully aged air at 100% equilibrium), 1 pCi/l equates to 0.01 WL. From the figure below, it can be seen that the alpha dpm rate on an alpha CAM filter *after equilibrium activities are established* is about 170 dpm per (pCi/l · lpm) at 1:1:1. For 1 pCi/l and 1 lpm, Eq (2) above yields $5.6x10^{-5} \cdot 170/1 = 0.00952$ or approximately 0.01 WL, as it should.**



Working Level (^{222}Rn) alone - cont.

- **To properly handle those time periods prior to the establishment of equilibrium activities, the time dependency of the build-up to equilibrium activities must be considered. This time dependency is typically well represented by a ($1-e^{-\lambda t}$) correction, which is applicable to instantaneous rates and to approximations of those rates from integration (i.e., CAM 'window') times which are quite small with respect to the shape of the build-up curves, allowing the determination of WL(t) as a function of time. Then Eq. (2) becomes:**

$$WL(^{222}Rn) = 5.6 \times 10^{-5} \cdot cpm_{\alpha} \; / \; [F(lpm) \cdot \varepsilon_{\alpha} \cdot (1-e^{-0.0195 \cdot t(min)})] \qquad (3)$$

where an effective $T_{½}$ of 35.5 min derives from the previous figure.

Working Level (^{222}Rn) - cont.

- **Next, for an alpha CAM utilizing alpha spectrometry, the 6.002 MeV and 7.69 MeV alpha count rates can be independently measured. Hence, the appropriate constants become 6.002 MeV/alpha dis per 1.3×10^{5} MeV/WL-liter = 4.6×10^{-5} WL-l/alpha dis for the 6.002 MeV alpha, and as previously shown above, 5.9×10^{-5} WL-l/alpha dis for the 7.69 MeV alpha. This then yields:**

$$WL(^{222}Rn) = [1/F \cdot \varepsilon] \cdot \{[4.6 \times 10^{-5} \cdot cpm_{6.002}/(1-e^{-0.224t})] + [5.9 \times 10^{-5} \cdot cpm_{7.69}/(1-e^{-0.195t})]\} \quad (4)$$

where:

- **$cpm_{6.002}$ is the count rate of the 6.002 MeV alpha,**
- **$cpm_{7.69}$ is the count rate of the 7.69 MeV alpha,**
- **Note that a λ value of 0.224 min^{-1} is applicable to the build-up of equilibrium 6.002 MeV alpha activity, corresponding to the $T_{½}$ of 3.098 min for ^{218}Po. The effective $T_{½}$ of 35.5 min is still acceptable for the remaining progeny sum (i.e., the RaB/RaC composite).**

Working Level (^{222}Rn) - cont.

Example 2: **To test this relationship, it is again known that at a 1:1:1 ratio (i.e., fully aged air at 100% equilibrium), 1 pCi/l equates to 0.01 WL. From Figure 1, it can be seen that the alpha dpm rate on an alpha CAM filter *<u>after equilibrium activities are established</u>* is about 170 dpm total per (pCi/l · lpm) at 1:1:1, about 10 dpm from the 6.002 MeV alpha and 160 dpm at 7.69 MeV. For 1 pCi/l and 1 lpm, Eq (4) yields $4.6 \times 10^{-5} \cdot 10 + 5.9 \times 10^{-5} \cdot 160 = 0.0099$ WL, as it should. (Remember that 101.1 pCi/l at equilibrium actually yields 1 WL.)**

Working Level (^{220}Rn)

- **Regarding WL(Tn) measurements, a simple alternative to standard methods, which are based on concentration determinations, can also be readily developed. The standard methods use the following relationship between thoron WL and progeny concentrations:**

$$\mathrm{WL(Tn)} = 0.134 \cdot \{\, 0.913[\mathrm{ThB}] + 0.087[\mathrm{ThC}] \,\} \qquad (5)$$

- **A relationship, similar to that previously developed in Eq. (2) for ^{222}Rn progeny, can readily be developed for ^{220}Rn progeny as well. In the thoron decay chain, a 64% branching ratio leads to the 8.78 MeV alpha, whereas a 36% branching ratio leads to an average energy from ^{212}Bi of 6.05 MeV. All together, this is equivalent to an effective alpha energy of 7.803 MeV, which then leads to a constant of $6.0\mathrm{x}10^{-5}$ in a similar equation for thoron WL when the applicable gross alpha cpm is the sum under the 6 MeV peak plus the 8.78 MeV peak.**

Working Level (^{220}Rn) alone - cont.

- **In other words, from a *gross* alpha CAM, WL(Tn) = 6.0x10^{-5} · alpha dis/liter, or**

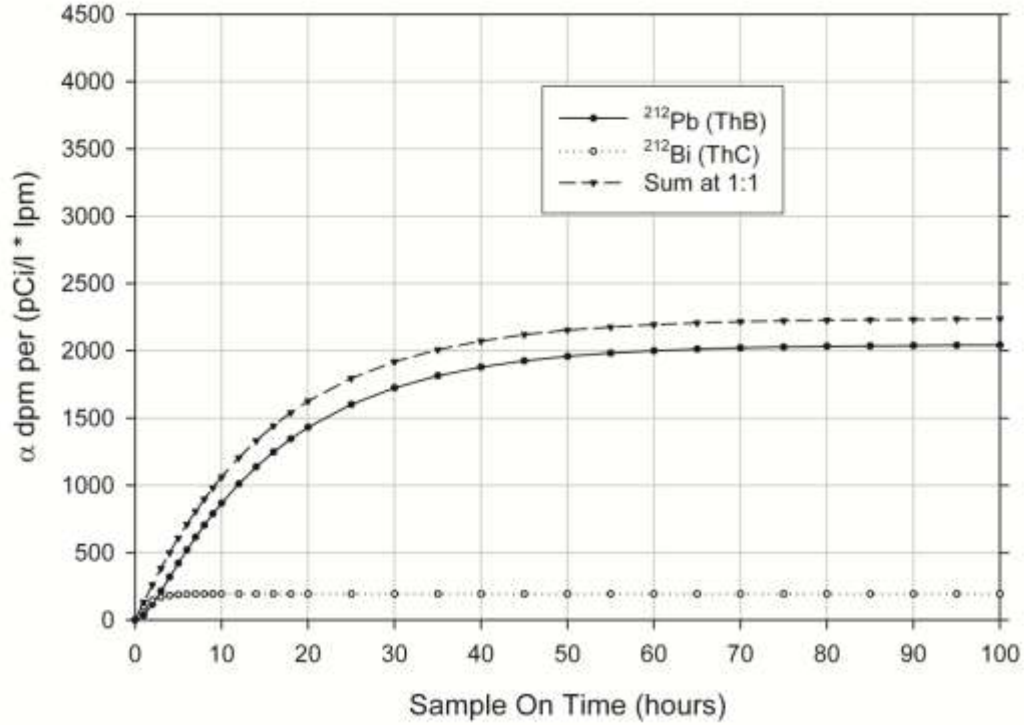
$$WL(^{220}Rn) = 6.0\times10^{-5} \cdot cpm_{\alpha} \;/\; [F(lpm) \cdot \varepsilon_{\alpha}] \qquad (6)$$

where:

- **cpm_{α} is the *gross* alpha count rate from thoron progeny,**
- **F is the air sampling flow rate in lpm, and**
- **ε_{α} is the alpha counting efficiency in counts per dis.**

Working Level (^{220}Rn) alone - cont.

Example 3: To test this relationship, it is known that at a 1:1 ratio (i.e., fully aged air at 100% equilibrium), 1 pCi/l equates to 0.134 WL. From the figure below, it can be seen that the alpha dpm rate on an alpha CAM filter *after equilibrium activities are established* is about 2236 dpm per (pCi/l · lpm) at 1:1. For 1 pCi/l and 1 lpm, the eqn above yields $6x10^{-5} \cdot 2236/1 = 0.134$ WL, as it should.



Working Level (^{220}Rn) alone - cont.

- **To properly handle those time periods prior to the establishment of equilibrium activities, the time dependency of the build-up to equilibrium activities must again be considered. This time dependency is well represented by a $(1-e^{-\lambda t})$ correction, allowing the determination of WL(t) as a function of time. Then Eq. (6) becomes:**

$$WL(^{220}Rn) = 6.0\text{x}10^{-5} \cdot cpm_{\alpha} \; / \; [F(lpm) \cdot \varepsilon_{\alpha} \cdot (1-e^{-0.001069 \cdot t(min)})] \qquad (7)$$

where an effective $T_{½}$ of 10.81 h derives from the previous figure.

WL(^{222}Rn) plus WL(^{220}Rn)

- **An alpha CAM utilizing alpha spectrometry could of course once again do better, treating each alpha separately, and therefore measure WL(Tn) and WL(Rn) simultaneously.**
- **WL(Tn) determinations can readily utilize the 8.78 MeV peak area alone. When normalized to the 8.78 MeV count rate alone, the factor in Eq. (7) becomes 6.0/0.64. This yields a new factor of 9.4x10^{-5}. Additionally, it must be understood that the time, t, is referenced to the start of air flow through the filter media. The resulting equation then takes the form:**

$$WL(^{220}Rn) = 9.4\times10^{-5} \cdot cpm_{8.78} \;/\; [F(lpm) \cdot \varepsilon_{\alpha} \cdot (1-e^{-0.001069 \cdot t(min)})] \quad (8a)$$

where:

- **$cpm_{8.78}$ is the count rate for the 8.78 MeV alpha only, and**
- **all other values are unchanged.**

WL(^{222}Rn) plus WL(^{220}Rn) – cont.

- **Note that 0.561 times this 8.78 MeV cpm value (i.e., 0.36/0.64) will need to be subtracted from the 6 MeV peak area values to leave just that count rate due to the radon progeny (i.e., ^{218}Po). This then leads to a slight modification of Eq. (3) as follows:**

$$WL(^{222}Rn) = 5.6\text{x}10^{-5} \cdot cpm_{6\&7.69,corr.} \;/\; [F(lpm) \cdot \varepsilon_{\alpha} \cdot (1-e^{-0.0195 \cdot t(min)})] \qquad (8b)$$

where:

- **$cpm_{6\&7.69,corr.}$ is the sum of the 6 MeV plus 7.69 MeV alpha peaks minus 0.561 times that at the 8.78 MeV peak, and all other values are unchanged from previous.**

WL(^{222}Rn & ^{220}Rn), i.e., WL(total)

- **An alpha spectroscopy CAM could also be utilized to measure the so-called total working level (due to both radon and thoron), *without the independent determination* of working level radon and/or working level thoron. *After the build-up of equilibrium activities*, the equation resulting from the application of fundamental principles and definition of WL takes the simple form:**

$$WL(total)= [1/F\cdot\varepsilon\cdot 1.3x10^{5}] \cdot [(6\cdot cpm_{6.002}) + (7.69\cdot cpm_{7.69}) + (8.78\cdot cpm_{8.78})] \quad (9)$$

where:

- **cpm_{6} is the count rate of the unresolved 6 MeV alpha peak,**
- **$cpm_{7.69}$ is the count rate of the 7.69 MeV alpha peak, etc.**
- **Eq. (9) is identical to the Total WL used in the Eberline Alpha-6A CAM with the Rn/Tn chip set installed (Eberline 1991).**

WL(^{222}Rn & ^{220}Rn), i.e., WL(total) – cont.

- **However, to properly handle those time periods prior to the establishment of equilibrium activities, the time dependency of the build-up to equilibrium activities must once again be considered. Additionally then, the thoron progeny counts at 6 MeV must be removed from the 6 MeV total count by subtracting 0.561 times the counts observed at the 8.78 MeV peak, similar to that in Eq. (8) above:**

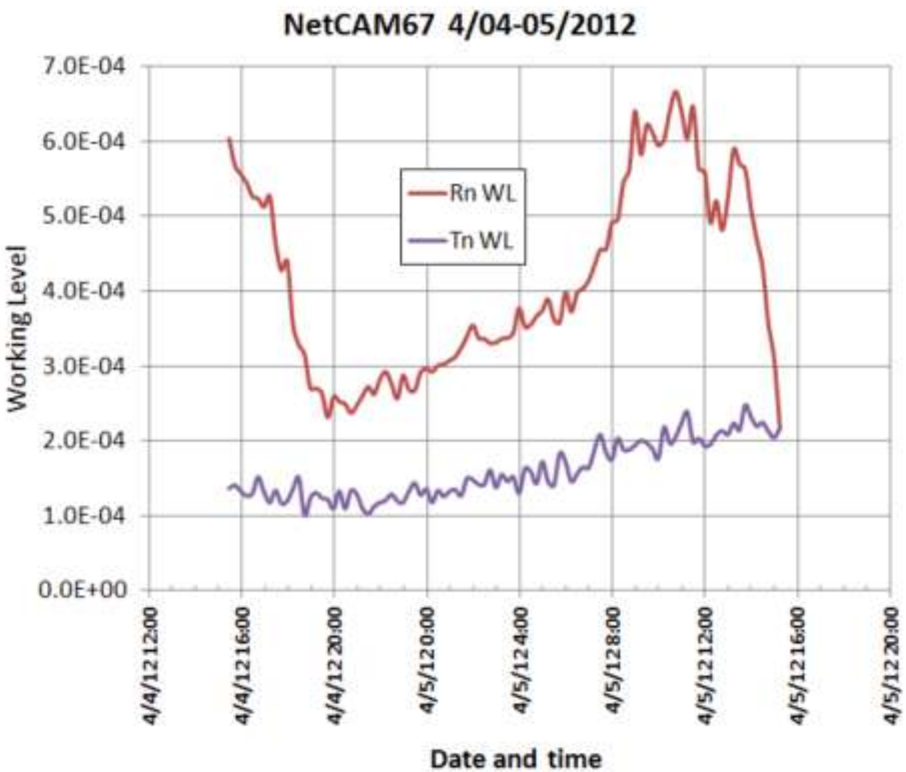
$$WL(total)= [1/F\cdot\varepsilon\cdot 1.3x10^5] \cdot [(6\cdot cpm_{6,corr.})/(1-e^{-\lambda_1 t}) + (7.69\cdot cpm_{7.69})/(1-e^{-\lambda_2 t}) + (12.22\cdot cpm_{8.78})/(1-e^{-\lambda_3 t})] \quad (10)$$

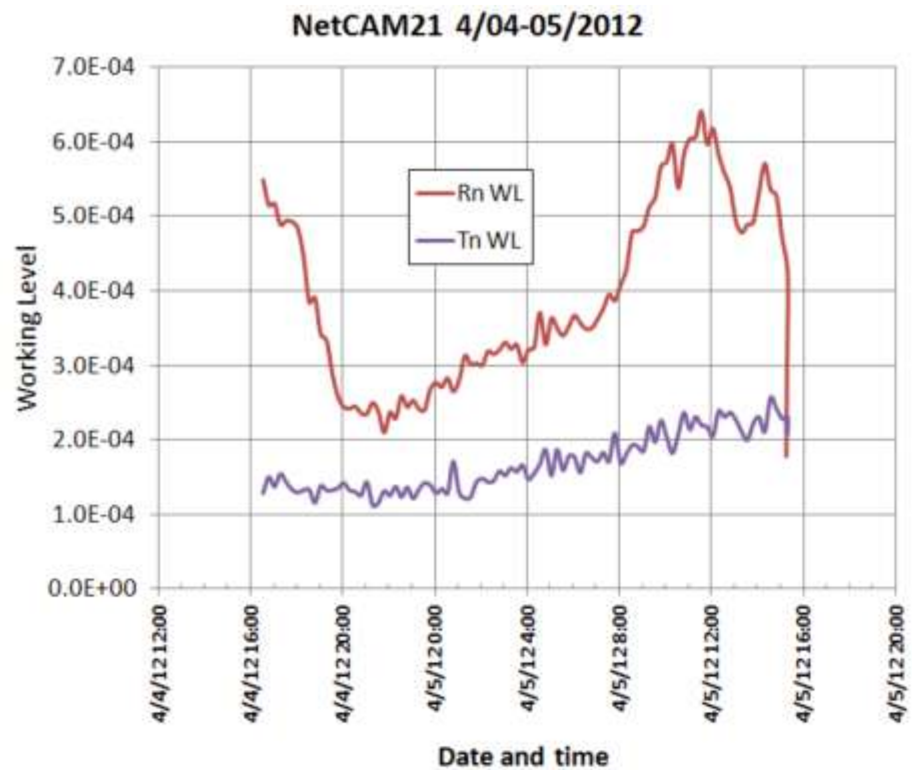
where λ_1=0.224, λ_2=0.0195, and λ_3=0.001069 min^{-1}, $cpm_{6,corr.}$ is the count rate of the 6 MeV alpha peak, corrected for the thoron contribution, etc.

- **Note that the λ_1 value corresponds to the $T_{½}$ of 3.098 min for ^{218}Po, the λ_2 value to an effective $T_{½}$ of 35.5 min (still applicable to the remaining bulk ^{222}Rn progeny sum), and the λ_3 value to an effective $T_{½}$ of 10.81 h, applicable for the Tn progeny sum.**

WL(Rn) and WL(Tn) – cont.

Actual measurements from Tom McLean, LANL:





WLM

- **Note that WL $\propto$ dpm$_\alpha$ (for example: WL(Rn)=[5.6x10^{-5}/F(lpm)] x dpm$_\alpha$).**
- **Hence, WL-min $\propto$ dis$_\alpha$. This would then yield, for example:**

  WL-min (Rn) = 5.6x10^{-5} · dis$_\alpha$ / F(lpm) (11a)

- **For WLM, the WL-min would be multiplied by the conversion factor of (1 hour/60 min)x(1 WM/170 hour) = 9.8x10^{-5}. Hence, for example:**

  WLM (Rn) = 5.6x10^{-5} · (9.8x10^{-5}/F) · (counts$_\alpha$ / ε_α) (11b)

  where counts$_\alpha$ are the total integrated counts from the filter replacement time onward.

WLM – cont.

Example 4:

- **Let's now consider a portable EPCAM used at a low flow rate as a WLM dosimeter for miners.**
- **Now note that if the integral counts were integrated from the filter replacement time (i.e., 8:00 AM Monday) only up to the end of the exposure (i.e., 5:00 PM Friday), then disintegrations would be lost post exposure. If, however, the EPCAM kept sampling in a background area until 8:00 AM Monday, then those disintegrations would be mostly counted, and the filter changed at that time.**
- **Hence, no $1/(1-e^{-\lambda t})$ correction should ever be necessary for the WLM mode of operation.**
- **A 'control' EPCAM should be left continuously in the background area, and its integrated WLM exposure subtracted from the other EPCAMs in use. (The EPCAMs in use should also be sampling overnight M-F in the control location as well.)**

WLM(Rn) and WLM(Tn)

- **For WLM(^{222}Rn), the actual equation to use is:**

$$WLM(Rn) = 5.6x10^{-5} \cdot (9.8x10^{-5}/F) \cdot (counts_{6\&7.69,corr.} / \varepsilon_{\alpha}) \quad (12a)$$

where:

$counts_{6\&7.69,corr.}$ is the sum of all integrated counts under the 6 MeV plus 7.69 MeV peaks minus 0.561 times that under the 8.78 MeV peak.

- **For WLM(^{220}Rn), the actual equation to use is:**

$$WLM(Tn) = 9.4x10^{-5} \cdot (9.8x10^{-5}/F) \cdot (counts_{8.78} / \varepsilon_{\alpha}) \quad (12b)$$

where:

$counts_{8.78}$ is the sum of all integrated counts under the 8.78 MeV peak only.

WLM(Rn) and WLM(Tn) – cont.

- **Example 5:**

  To test Eq. (12a), it is known that at a 1:1:1 ratio (i.e., fully aged air at 100% equilibrium), 1 pCi/l for 170 h equates to 0.01 WLM. With 170 dpm per (pCi/l · lpm) at 1:1:1, 170 hours of sampling implies 1.734×10^{6} dis at 1 pCi/l and 1 lpm. Eq. (12a) above then yields:

  $$\text{WLM(Rn)} = 5.6 \times 10^{-5} \cdot (9.8 \times 10^{-5}/1) \cdot 1.734 \times 10^{6} = 0.0095 \text{ WLM}$$

  or approximately 0.01 WLM, as it should.

- **Example 6:**

  To test Eq. (12b), it is known that at a 1:1 ratio (i.e., fully aged air at 100% equilibrium), 1 pCi/l for 170 hours equates to 0.134 WLM. With 2236 dpm per (pCi/l · lpm) at 1:1, 170 hours of sampling implies 2.281×10^{7} dis at 1 pCi/l and 1 lpm. Eq (12b) then yields:

  $$\text{WLM(Tn)} = 9.4 \times 10^{-5} \cdot (9.8 \times 10^{-5}/1) \cdot (0.64 \cdot 2.281 \times 10^{7}) = 0.134 \text{ WLM}$$

  as it should.

Bonus Material – WL grab sample analysis

- **A WL grab sample was pulled at 42.5 lpm during Tom McLean's CAM data.**

Table 1. Conversion factors (as dpm per WL·lpm) for the two sampling regimes versus the average age of air (min) and, equivalently, the effective ventilation exchange rate (h^{-1}).

		Modified Rolle	Generalized Kusnetz
		T_S = 5 min	T_S = 5 min
		T_W = 4 min	T_W = 40 min
		T_C = 5 min	T_C = 5 min
Average Age of Air (min)	Effective Ventilation Exchange Rate (h^{-1})		
5	12	1397.5	597.2
10	6	1219.7	658.8
20	3	1088.0	715.2
30	2	1074.0	733.3
40	1.5	1091.9	738.7
50	1.2	1116.4	739.7
60	1	1140.1	739.0
120	0.5	1222.5	732.3
180	0.33	1246.0	729.7
240	0.25	1251.8	729.0
	Median(±Span%):	1235.8(±13.1%)	668.5(±10.6%)

Note that T_S is the sampling time, T_W is the waiting time, and T_C is the count time.

Bonus Material – average age of air

- **The average age of air is reflected in Tom's α spectroscopic data!**
- **The $dpm_{7.69}$/ $dpm_{6.002,corr.}$ ratio was about 6, corresponding to about 30-minute air.**

Average Age of Air (minutes)	Effective Ventilation Exchange Rate ($hour^{-1}$)	Ratio of $dpm_{7.69}$ / $dpm_{6.002}$ (after equilibrium activities are established)
1	60	1.100
2	30	1.224
5	12	1.644
10	6	2.475
15	4	3.411
20	3	4.386
30	2	6.283
40	1.5	7.985
50	1.2	9.451
60	1	10.69
75	0.8	12.16
90	0.66	13.26
120	0.5	14.63
150	0.4	15.33
180	0.33	15.67
240	0.25	15.92
∞	0	15.99

Bonus Material – grab sample vs. CAM results

- The modified Rolle count was 27.2 dpm (based on 53 α counts). The WL(Rn) determination then yields:

  27.2 dpm/(1074 dpm/WL-lpm x 42.5 lpm) = 0.596 mWL

- The generalized Kusnetz count was 18.4 dpm (based on 36 α counts). The WL(Rn) determination then yields:

  18.4 dpm/(733.3 dpm/WL-lpm x 42.5 lpm) = 0.59 mWL

- Tom's CAM data indicated a WL(Rn) value of about 0.6 mWL at the time of the grab sample.

Bonus Material – effective ventilation

Paper

EVALUATION OF CONTINUOUS AIR MONITOR PLACEMENT IN A PLUTONIUM FACILITY

Jeffrey J. Whicker,* John C. Rodgers,* Charles I. Fairchild,† Ronald C. Scripsick,† and Ricky C. Lopez†

Health Physics May 1997, Volume 72, Number 5

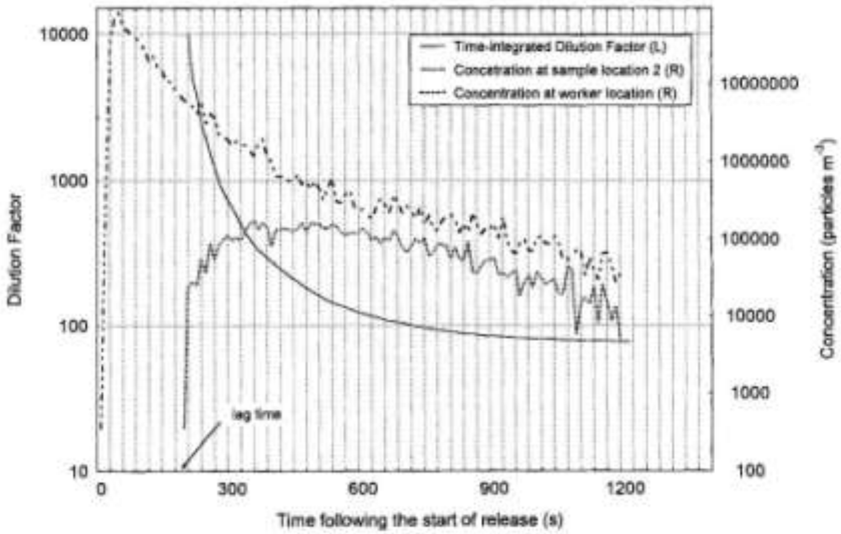


Fig. 7. Concentrations for worker and sample locations and the corresponding time-integrated dilution factors over time for a release in room 420.

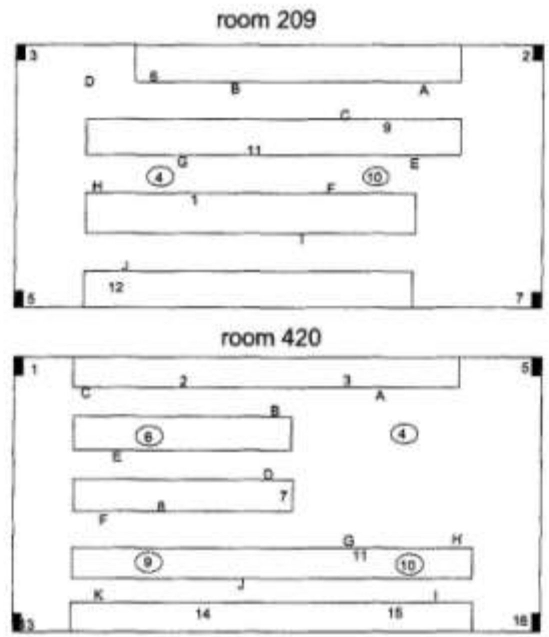
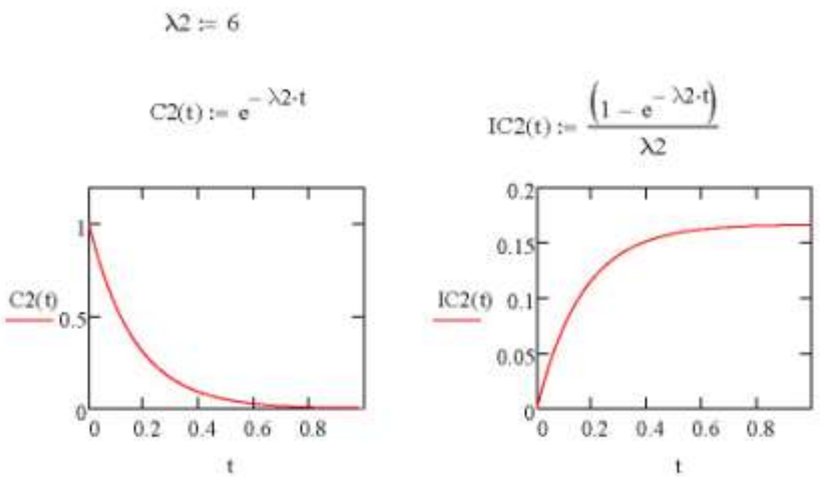


Fig. 1. Approximate position of sample, release, and ventilation supply and exhaust locations in test rooms. Numbers represent sampling positions and letters represent release positions. Open rectangles are glovebox lines and ovals indicate position of supply diffusers on the ceiling. Wall-mounted, floor-level exhaust points are shown by the shaded rectangles in the corners.

Bonus Material – dose reduction vs λ_{vent}



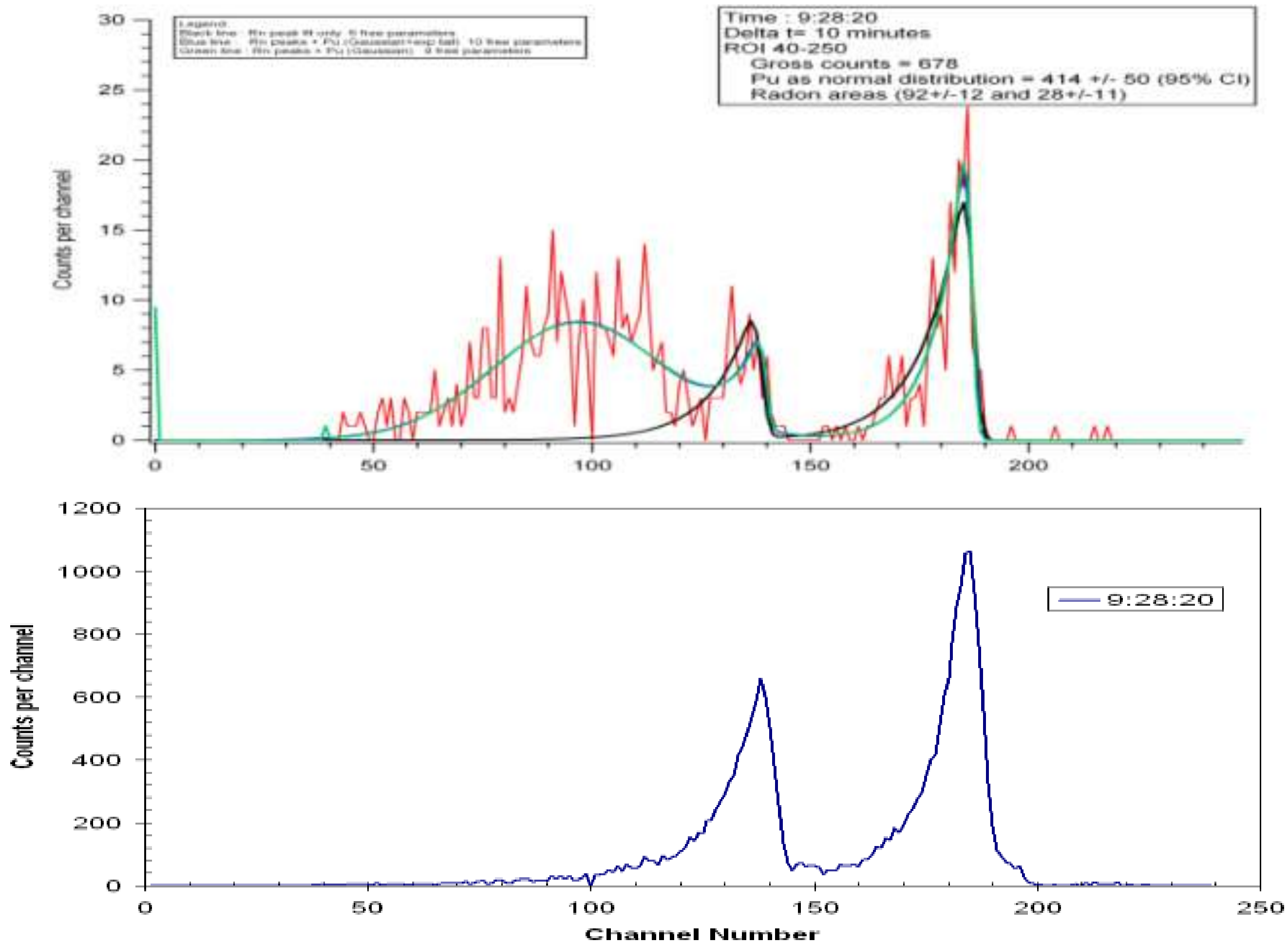
- $0.1 = 1 - \exp(-\lambda t_{0.1}) \rightarrow \; t_{0.1} = 0.105/\lambda = 0.105 \cdot \tau$
- **So the maximum time between Slow alarm decisions should be about 10% of the average age of air (based on Puff releases).**
- **For the most affected nose, $\lambda_{man} = 5\lambda$, and the maximum time between Fast alarm decisions should be 5 times faster than the Slow.**

Bonus Material – CAM response & alarm times

Average Age of Air (minutes)	Effective Ventilation Exchange Rate ($hour^{-1}$)	Ratio of $dpm_{7.69}$ / $dpm_{6.002}$ (after equilibrium activities are established)	Max. Time between Alarm Decisions (min) – based on puff release alone
1	60	1.100	0.11
2	30	1.224	0.21
5	12	1.644	0.53
10	6	2.475	1.1
15	4	3.411	16
20	3	4.386	2.1
30	2	6.283	3.2
40	1.5	7.985	4.2
50	1.2	9.451	5.3
60	1	10.69	6.3
75	0.8	12.16	7.9
90	0.66	13.26	9.5
120	0.5	14.63	
150	0.4	15.33	
180	0.33	15.67	
240	0.25	15.92	
∞	0	15.99	

- **Sliding Differential mode - i.e., 10-min window / ≈1-min march step**
- **Blind Man's Differential mode - i.e., 1.1-minute window (≡ march step)**
- **Full Cumulative mode - ≈1-min Slow march step / ≈12-sec Fast step**

Bonus Material – equil. ratios at 6 h^{-1}



End of Presentation

- **Questions?**