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Field Validation Study of the MDA® Instant Working Level Meter in a High Gamma Background Mine Environment

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Accurate and reproducible radon daughter measurements are essential to protect workers in the mining industry and assure compliance with federal regulations. The precision and accuracy of the MDA® Model 811 Instant Working Level Meter (IWLM) has been questioned when it is used in a high gamma environment of an underground uranium mine due to the increased statistical uncertainty associated with the background radiations. Comparative side by side sampling at a single underground mine station exhibiting a 3.0 mR/h "gamma background" was conducted utilizing the IWLM, the Kusnetz and the Tsivoglou methods. A total of fifty sets of samples were taken, with half using an unshielded IWLM and the other half using a lead shield to reduce the effect of the high gamma background radiation. IWLM, Kusnetz and "baseline" Tsivoglou measurements were then analyzed. A significantly large error was associated with the IWLM in both the shielded and unshielded data groups.

Introduction

Radiation surveys constitute an important part of the work of health and safety personnel in their efforts to assure a healthy and safe mine environment. Although uranium mines are the focus of these surveys, it should be noted that radiation hazards also exist in many non-uranium mines.

The present technique for measuring worker exposure is time consuming. Mine operators would prefer a simpler procedure if accuracy were not compromised.

In response to demands for a method which will yield a suitable measurement in a relatively short period of time, several procedures have been suggested.[(1-3)] Various "Instant Working Level Meters" (IWLM) have been developed and tested.[(4)] The first IWLMs were bulky and not sufficiently reliable. Furthermore, the precision of 50 to 100 percent in the early measurements was unsatisfactory.

However, a new group of IWLMs have evolved and been tested to varying degrees.[(3,5)] Within this group is the MDA Model 811 IWLM, which is a compact, portable instrument weighing approximately 5 kg. All sampling steps are controlled by light-emitting diodes (LEDs) on the front panel. Air is drawn at 2.5 Lpm for two minutes through a glass fiber filter inserted in a specially designed filter holder which is then placed in the IWLM receptable. After a 30-second delay, the alpha and beta activities are counted for one minute and a WL determined.[(6)] Due to its portability (5 kg) and three and one-half minute sampling time, this instrument drastically reduces the required time of current sampling procedures and greatly enhances both the personnel and control strategies of a radiation program. Limited studies of precision and accuracy have been conducted for this instrument, but no consideration has been given to high gamma background environments. Since the instrument utilizes a beta detector (Pilot B), which is gamma sensitive, MDA has recommended tungsten shielding in environments where gamma background exceeds 1.0 mR/h or 0.7% U_3O_8. This recommendation is not based on any published research.

The objective of this study was to determine the effect of a high gamma (3.0 mR/h) background on the accuracy and precision of the MDA Model 811 IWLM and the effect of lead (Pb) shielding.

Measurement Methods

Radiation exposure was measured with a shielded and an unshielded MDA Model 811 and compared with results of the more commonly used techniques which are time consuming. The unit of comparison was the "Working Level" (WL). It is employed throughout the world as a unit of radon decay product concentration. A WL is considered to be any combination of short-lived decay products of radon which result in the emission of 1.3×10^5 MeV of alpha energy per liter of air.[(7)] The unit was proposed in 1957 by the United States Public Health Service (USPHS) after recognition that radiation exposure to miners was predominantly due to radon decay products. The radon gas itself has a longer half-life and provides a minimal dosage amount. Therefore, this unit takes no notice of the activity of radon gas. The WL is concerned only with the alpha energy emitted from the subsequent nuclides. The U.S. Secretary of Labor promulgated a standard of 12 Working Level Months (WLM) per year with later reductions to a standard of 4 WLM per year. The accumulated Working Level Hours (WLH), the WL multiplied by the number of hours spent in each particular concentration, are divided by the average number of hours worked in a month (173) to calculate WLM.[(7)]

The American National Standards Institute (ANSI) has published a "consensus standard" for radiation protection in uranium mines.[(8)] According to this standard, a monitoring system for radon daughters must be capable of measuring the annual accumulated exposure in WLM with an uncertainty interval of 50 percent at the 95 percent confidence level.

In order to measure the WL in a mining atmosphere, three independent quantities (RaA, RaB and RaC) have to be determined and many methods have been proposed. The best accuracy is obtained when all three are measured independently.[9,10,11] However, several designs have been developed which derive the WL from only two measurements, or by a single gross alpha measurement.[1,2,12-14]

In-mine samples are collected by pumping a known volume of air through a filter which collects the radon daughters whose activity is then measured with a suitable detector. A scintillometer and scaler are normally used.

The Kusnetz Method

The method used almost exclusively in mines to determine WL is the Kusnetz method developed in 1956.[13] It is a "one measurement" technique that requires filtering a predetermined volume of air. A five-minute sample at a flowrate of two Lpm was used. After waiting for 40 to 90 minutes, a measurement of gross alpha activity was taken for one minute. The WL was then calculated by:

$$WL = \frac{GCTS - BG}{KET_s V} \quad (1)$$

where GCTS = gross counts per minute,
BG = background counts,
K = Kusnetz factor,
T_s = sampling time in minutes,
V = flowrate in Lpm, and
E = counter efficiency.

The Modified Tsivoglou Method

The "modified Tsivoglou" method for the measurement of radon daughters is based on counting the alpha activities of filtered air samples over set time intervals.[15] A sampling time of five minutes followed by three counting intervals was selected. The first counting interval was 2 to 5 minutes after the end of sampling. The second interval was then 6 to 20 minutes and the third and last interval ran from 21 to 30 minutes. To obtain air concentrations of RaA, RaB and RaC directly from time interval counts, Thomas[15] applied the Bateman equations to yield:

$$C_2 = \frac{1}{VE}(0.16894\ X_{2,5} - 0.08200\ X_{6,20} + 0.07753\ X_{21,30}) \quad (2)$$

$$C_3 = \frac{1}{VE}(0.00122\ X_{2,5} - 0.02057\ X_{6,20} + 0.04909\ X_{21,30}) \quad (3)$$

$$C_4 = \frac{1}{VE}(-0.02252\ X_{2,5} + 0.03318\ X_{6,20} - 0.03771\ X_{21,30}) \quad (4)$$

where C_2, C_3, and C_4 = concentrations of RaA, B and C in pCi/L,
V = sampling rate in liters per minute,
E = alpha counter efficiency in counts per minute divided by the actual disintegrations per minute, and
$X_{i,j}$ = counts obtained during the specified time interval indicated by the subscripts i and j.

The equation for WL in terms of the individual nuclide concentration is:

$$WL = 0.00103\ C_2 + 0.00507\ C_3 + 0.00373\ C_4 \quad (5)$$

"Precision" of more than 2 percent is found in the 0.5 to 1.0 WL range.[16]

The IWLM Method

During the IWLM pumping cycle, the Model 811 takes a background count during the first minute. This gives some indication of the background gamma radiations and is used in the WL counting cycle as a means of instrument discrimination between gamma and beta radiations. At the end of that count, a "READ" LED is illuminated. At this time, the background readings are recorded. After the two minute sampling cycle has concluded, the lighted "PUMP" LED goes off and the pump is shut off. The filter is then transferred to the IWLM counting chamber. The alpha and beta activities are counted over a one-minute period that extends from 2.5 to 3.5 minutes after the sampling began. The "READ" LED once again lights and the alpha and beta readings are recorded. These two readings are added together to give the IWLM WL measurement.

The Mine Experiment Method

The study was conducted at a single underground station in a Colorado uranium mine with a measured gamma background of 3 mR/h ± 10%. In order to address the most critical levels of exposure and to minimize instrument error, the range of measurements was limited to 0.33 WL or greater. Lower values may reduce the correlation between the Tsivoglou and IWLM values due to the increased statistical counting errors involved.

Two sets of side by side samples were established. One consisted of 25 concurrent MDA, Kusnetz and Tsivoglou measurements utilizing an unshielded MDA Model 811 and the second was taken using 6 mm (0.25-inch) lead shielding for the MDA which resulted in a measured 10 percent reduction in gamma background.

TABLE I
Average Working Level Measurements of Tsivoglou, Unshielded IWLM and Kusnetz Measurement Techniques[A]

	Tsivoglou	Unshielded IWLM	Kusnetz
Range	0.27-1.17	0.33-1.43	0.31-1.20
Mean ($\bar{x}$)	0.69	0.96	0.67
Standard Deviation (SD)	0.28	0.32	0.28
Coefficient (CV) of Variation (%)	40.6	33.3	41.8
Error (%)		+38.3	−2.8

[A]Number of samples = 25.

In order to minimize other variables, samples were taken in an area of the mine where optimal control of ventilation, minimal mining activity and easy accessibility were possible. Ventilation was controlled by doors located near the intake air shaft which governed all fresh air coming into the sampling area. This enabled the study to be conducted with minimal ventilation fluctuations and at levels exceeding 0.33 WL, in order to reduce statistical counting errors.[5]

A sampling station was placed in a suitable location at the site. Gamma background using an Eberline® Model E-120 geiger counter was 2.8 to 3.2 mR/h. In order to insure consistency of sampling, the instrument arrangement at the station remained constant throughout the experiment.

The comparative sampling was conducted from May 10th to 21st, 1982. Each concurrent sampling consisted of two air samples, one for the Kusnetz and Tsivoglou value and one for the IWLM. A ten-liter sample at a flow rate of 2 Lpm for five minutes was taken for the Kusnetz and Tsivoglou methods. Secondly, the recommended five-liter sample for the IWLM method was drawn at 2.5 Lpm for a two-minute period. The two pumps were started simultaneously. Strict control of the ventilation doors was maintained throughout the sampling cycles in order to minimize error introduced by fluctuations in radon levels. The time intervals for the IWLM pump cycle and counting periods were controlled by the instrument LEDs, while those for the Tsivoglou and Kusnetz measurements were controlled manually using a stopwatch. When variations of ventilation, miscounting of activities or any other known error occurred, the sample was immediately terminated and repeated.

Calibration

In preparation for sampling, three MSA Model S pumps were calibrated at the mine site. The pumps had been fully charged and run for 30 minutes prior to calibration allowing for stabilization of the nickel-cadmium batteries. A one-liter burette system was used to calibrate the sampling train. An in-line, Gelman®, Type A/E glass fiber filter and holder were incorporated. Each pump was calibrated at a flow of 2.0 and 2.5 Lpm to facilitate the two necessary flowrates to be used in the sampling. Because of the different sampling heads used, the lengths of tubing in the sampling train were adjusted so that the filters would be at the same height.

An Eberline Model PRS-2 Serial 341 scaler and SPA-1 scintillation detector with a Th-230 alpha source were submitted to the Mine Safety and Health Administration Radiation Branch facility in Lakewood, Colorado for calibration. Results from that calibration indicated that the instrument had a counting efficiency of 28 percent at an electrical output of 875 volts.

The MDA Model 811 IWLM Serial 780 was calibrated using the 811-alpha and beta standards supplied by the manufacturer. The IWLM was fully charged and had been run through five counting cycles for battery stabilization before calibration. A series of ten alpha and ten beta calibrations were taken and the instrument was within the recommended 5 percent range (actual +3% alpha, −0.9% beta). A blank counting cycle gave no indication of chamber contamination. During each sampling day, a field calibration of both the MDA and Eberline units was conducted.

Subsequent to the experimental sampling, a check of the sampling pumps was made to verify the calibration of the flowrates. The Eberline unit was also checked for its accuracy and calibration factors at the U.S. Bureau of Mines (USBM) Denver Research Center. A radon chamber is used for this purpose which is constantly monitored by a system developed by Droullard.[17]

Data Analysis

In order to avoid sampler bias, calculation of the Kusnetz and Tsivoglou concentrations was made after completion of all sampling. In calculating the Kusnetz readings, the following formula was used:

$$WL = \frac{3.7 \times CPM}{150 \times 10} \qquad (6)$$

where WL = working level,

3.7 = reciprocal of the counting efficiency of the instrument,

CPM = counts per minute,

150 = Kusnetz factor, and

10 = volume of air (in liters) pulled through the filter.

The Tsivoglou readings were calculated using the USBM computer program[16] giving the concentrations (pCi/L) of each daughter product, WLs and standard deviations of each measurement.

From the compiled data, overall mean concentrations ($\bar{x}$), standard deviations (SD) and coefficients of variation (CV) were calculated (Tables I and II). The range of both sample sets is large and represents WL concentrations which minimize the error caused by activity counting as suggested by Holub.[5] The highest degree of accuracy is given by the Kusnetz measurement method. Negative errors of three and six percent were exhibited by the Kusnetz method in this study. These findings confirmed the predictions of the USBM study and analysis of error bias of "young air" by Groer.[3,5]

TABLE II
Average Working Level Measurements of Tsivoglou, Shielded IWLM and Kusnetz Measurement Techniques[A]

	Tsivoglou	Shielded IWLM	Kusnetz
Range	0.24-1.10	0.39-1.26	0.23-1.04
Mean ($\bar{x}$)	0.64	0.84	0.60
Standard Deviation (SD)	0.24	0.23	0.24
Coefficient (CV) of Variation (%)	37.5	27.4	40.0
Error (%)		+31.3	−6.2

[A]Number of samples = 25.

Analysis of the unshielded IWLM data indicated a positive error of 39 percent over the Tsivoglou "baseline" readings. The lead (Pb) shielding of the instrument provided an eight percent improvement in accuracy. However, the shielded instrument still had a positive error of 31 percent. If the accuracy requirement of the MSHA testing is applied, which required the IWLM to be within ± 10% of the Tsivoglou readings or as accurate as the Kusnetz method, the results of this test are not favorable.[18] If the error above the predicted 15 percent error map analysis is attributed to gamma background, 24 percent is due to the high background radiations encountered.[19] Contributing factors associated with this error include: the statistical uncertainty generated by a high number of background counts, the beta counting efficiencies incorporated in the IWLM circuitry used to calculate the WL measurements, and the ability of the beta detector to discriminate between the gamma and beta energies which fall within a common MeV range. The coefficients of variation indicate that the reproducibility of the IWLM was better than those of the Tsivoglou or Kusnetz methods. Shielding had a positive effect on this analytical indicator. Comparison of the proportional changes between the Tsivoglou and IWLM coefficients in the unshielded versus shielded data verify this factor.

In order to verify the significance of the IWLM and Kusnetz data to the "baseline" Tsivoglou readings, a paired t-test was conducted.[20] The following formulas were used to compute the experimental values (Table III):

$$t_{exp} = \frac{\bar{n}_1 - \bar{n}_2}{s} \sqrt{\frac{m_1 - m_2}{m_1 + m_2}} \quad (7)$$

TABLE III
Paired t-Test of Set Data at 95% Confidence Level

Set Methods	Working Levels $\bar{x}^A$	SD^B	t_{exp}^C
Unshielded IWLM-	0.96	0.32	
Tsivoglou	0.69	0.28	
			6.5
Shielded IWLM-	0.84	0.23	
Tsivoglou	0.64	0.25	
			5.3
Kusnetz-	0.67	0.28	
Tsivoglou (1)[D]	0.69	0.28	
			1.2
Kusnetz-	0.60	0.24	
Tsivoglou (2)[D]	0.64	0.25	
			3.6

[A]$\bar{x}$ = Mean.
[B]SD = Standard deviation.
[C]t_{exp} = Calculated experimental t-test statistic.
[D]Group (1) taken during unshielded test cycle; Group (2) accumulated during shielded test cycle.
df = Degrees of freedom = 48.
$t_{.025,48}$ = Test statistic = 2.0.

$$S = \sqrt{\frac{S_1^2 + S_2^2}{m_1 + m_2 - 2}} \quad (8)$$

where $\bar{n}$ = mean of data set,
S = mean square of the standard deviation, and
m = the number of measurements in each set.

When the t_{exp} is compared to the test statistic at the 95 percent confidence interval, it is apparent that more than random error is involved in both sets of IWLM data. The t-test of the first set of Kusnetz data indicated random error at the 95 percent confidence level. However, the second set of Kusnetz measurements showed significant error associated with the instrument readings, which could have been due to the radon daughter mixtures encountered.

A regression analysis was conducted in order to determine the linear relationship between the "baseline" Tsivoglou, IWLM and Kusnetz measurements. A regression model was derived in order to optimize or correct the IWLM readings in high gamma fields.

The appropriate calculations were performed for the corrected sums of squares of x (S_{xx}) and the corrected cross products of x and y (S_{xy}) using the following formulas:

$$S_{xx} = \sum_{i=1}^{n} x_i^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n} \quad (9)$$

$$S_{xy} = \sum_{i=1}^{n} x_i y_i - \frac{(\sum_{i=j}^{n} x_i)(\sum_{i=j}^{n} y_i)}{n} \quad (10)$$

From the calculations, the least squares estimates of the slope and intercept were computed and an estimated simple linear regression model was derived. The models found for the Tsivoglou versus Kusnetz methods were y = 0.93 x + 0.03 (R^2 = 0.89) and y = 0.93 x + 0.01 (R^2 = 0.96). The results for the Tsivoglou versus IWLM methods were y = 0.88 x + 0.36 (R^2 = 0.58) for the unshielded IWLM and y = 0.62 x + 0.44 (R^2 = 0.47) for the shielded unit (Figure 1). For the Kusnetz versus IWLM data, regression models of y = 0.88 x + 0.37 (R^2 = 0.56) for the unshielded IWLM and y = 0.63 x + 0.46 (R^2 = 0.43) for the shielded IWLM were calculated (Figure 2).

The regression and residual mean square values were calculated in order to determine the significance of the regression models. Experimental F values were compared to the critical F value (4.28) at 95 percent confidence (Table IV). If the experimental value of F_0 exceeds the critical F value, a linear relation exists between the slopes of the regression lines. A larger difference between F_0 and F indicates more significant linearity.

A strong linear trend is exhibited between the Kusnetz and Tsivoglou measurements. This fact could have been enhanced by the use of the same filter for both count methods. A weak linear trend also exists between the IWLM versus Tsivoglou readings according to the F statistic and considerable scatter is present (Figure 1). The least amount of linearity was indicated by the Kusnetz versus IWLM data (Figure 2).

The coefficient of determination (R^2) was calculated for all cases. (Table IV). This coefficient is loosely described as

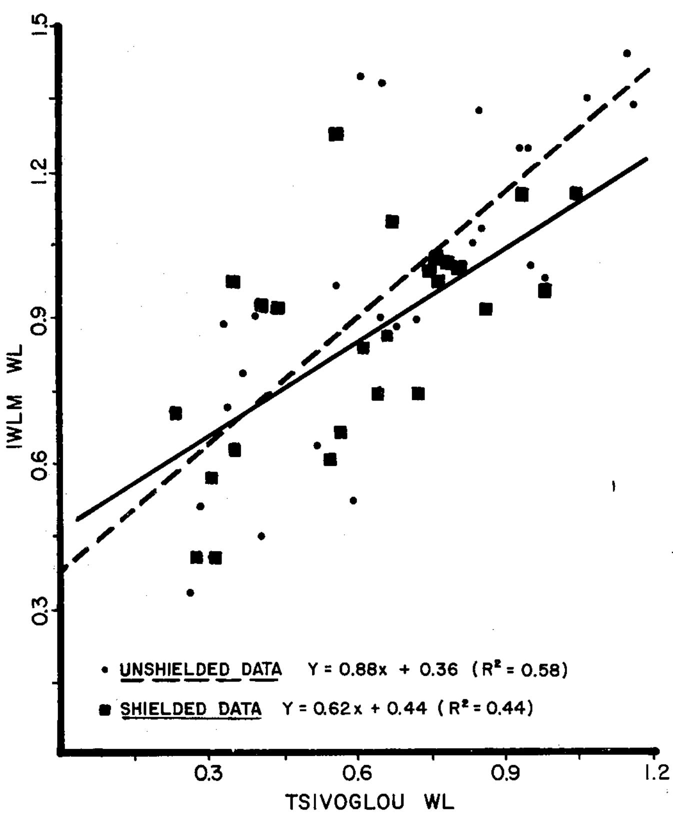

Figure 1 — Linear regression model of IWLM — Tsivoglou data showing individual sample points.

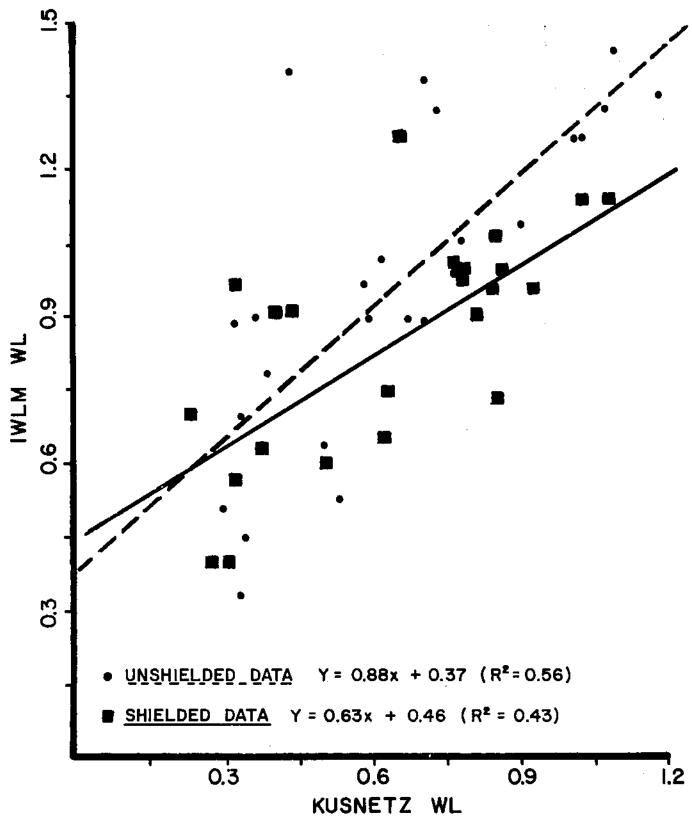

Figure 2 — Linear regression model of IWLM — Kusnetz data showing individual sample points.

the amount of variability in the data accounted for by the regression model.[21] R^2 values can range from 0.0 to 1.0, with more linear significance being associated with values approaching 1.0. Again, the strongest degree of linearity was exhibited by the Tsivoglou versus Kusnetz data followed by the IWLM versus Tsivoglou measurements. As in the previous analysis, the Kusnetz versus IWLM data showed the lowest degree of linearity.

TABLE IV
Linear Regression Analysis of Paired Measurement Data at 95% Confidence Level

Paired Methods	Slope	Y-Intercept	F_0[A]	R^2 [B]
Kusnetz-Tsivoglou (1)[C]	0.93	0.03	178.8	0.89
Kusnetz-Tsivoglou (2)[C]	0.93	0.01	502.8	0.96
Unshielded IWLM-Tsivoglou	0.88	0.36	31.6	0.58
Shielded IWLM-Tsivoglou	0.62	0.44	20.7	0.47
Unshielded IWLM-Kusnetz	0.88	0.37	29.7	0.56
Shielded IWLM-Kusnetz	0.63	0.46	17.3	0.43

[A]F_0 = Calculated test statistic.
[B]R^2 = Regression coefficient.
[C]Group (1) taken during unshielded test cycle; Group (2) accumulated during shielded test cycle.
F = Test statistic at 95% confidence = 4.28.

A pilot study was conducted at various times during the year prior to the initiation of this field evaluation (Table V). The samples were taken throughout the mine at different WL concentrations and gamma background levels. A different MDA IWLM was used and only Kusnetz measurements were calculated for comparison purposes. The mean gamma background was the same as that used in the field evaluation. The mean WL concentration also fulfilled the criterion used in the main study. The mean IWLM reading for the pilot study was very close to the mean Kusnetz measurement. Consequently, some or all of the difference between the IWLM and Tsivoglou concentrations in the main body of the study might be attributed to the particular instrument used, even though it was calibrated before and after testing. Of course, other sources of error, such as variations in the ventilation, impaction of radon daughters on the sampling instruments, filter absorption and varying degrees of radon decay associated with the sampled air could have contributed to the overall bias.

TABLE V
Averages of Pilot Study Results[A]

	IWLM (WL)	Kusnetz (WL)	Gamma (mR/h)
Range	0.03 - 2.99	0.02 - 2.59	1.0 - 7.0
Mean	0.46	0.48	3.0
SD	0.76	0.69	

[A]Number of samples = 23.

Summary and Recommendations

This field evaluation provides evidence showing a large degree of error associated with the IWLM in a 3.0 mR/h gamma background environment. The increased net counting rates associated with the high gamma background levels leads to a high statistical uncertainty in the instrument due to the gamma-sensitive characteristics of the IWLM beta detector. A slight improvement was provided by shielding the instrument with lead (Pb), but a 31 percent error still existed. The relationship between the IWLM WL values and the Tsivoglou data was moderately linear ($R^2 = 0.58$). When shielding was used, linearity decreased slightly ($R^2 = 0.43$).

Preliminary studies conducted by MSHA-USBM are contradictory to the results of this study.[22] Differences exist not only in the degree of error, but also in positive versus negative biases. These indications were supported by the pilot study results. However, both the MSHA-USBM and pilot studies were complicated by multiple sampling locations and/or multiple sampling personnel.[17,18] Additional research is necessary to resolve these questions.

Further analyses are needed in several areas. A large error may be associated with instrument malfunction. Adequacy of manufacturer calibration schemes should be analyzed for all environments which could be encountered. A Tsivoglou formula for a 5-liter volume with a 2-minute sampling period should be derived and tested. This would reduce error associated with air sampling and multiple filter counting. One filter could then be used to determine the Tsivoglou and IWLM WL measurements.

The tungsten shield recommended by MDA should be incorporated in future studies. Because the tungsten shield was very expensive ($3000), it was not used in this experiment and a cost-benefit analysis is recommended. The addition of this shield would increase the instrument cost by approximately 50 percent. To this date, such a shield has not been manufactured for the instrument.

The results of this study showed an unsatisfactory correlation between the IWLM and Tsivoglou sampling data. However, the IWLM measurements gave higher WL values in all but a few measurements and should be considered conservative. Since only one IWLM instrument was used in the study, these conclusions should not be extended to all IWLMs or even all MDA Model 811s.

If the instrument is to be used in a high gamma background area, the least squares fit equation of $y = 0.88 x + 0.36$ ($R^2 = 0.56$) should be used until further research is done in multiple levels of background radiation. The use of lead (Pb) shielding is not recommended. There is no significant improvement in the correlation to the Tsivoglou method and the weight drastically reduces its portability in a mine environment.

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