

IN-LINE MONITORING OF RADIUM SLURRY BY GAMMA-RAY SPECTROMETRY

S. A. Philips, Canberra Industries, Inc.

S. Croft, Canberra Industries, Inc.

ABSTRACT

The processing of uranium ores generates a waste product rich in radium. The waste product is mobilized into a liquid slurry form by mixing with water and is measured while being pumped around a re-circulation loop. In order to prepare the appropriate mix of slurry and hardening agents for the final disposal product, the radium concentration in the slurry must be determined in real time. We have developed an In-Line Monitor to provide density and radium concentration information for the slurry on a time scale on par with the re-circulation process.

The density of the slurry is determined from a transmission measurement using the 122 keV γ from ^{57}Co . The radium concentration in the slurry is determined from a direct measurement of the ^{226}Ra 186 keV emission using quantitative gamma-ray spectrometry. The concentration determination includes a self-attenuation correction factor obtained from the transmission measurement and uses the ratio of the mass attenuation coefficients of the slurry at the assay and transmission energies. The density and concentration results are presented as real-time rolling averages along with a full uncertainty analysis. Concentration values for other (daughter) nuclides may also be quantified in the same measurement. Presented here are the main features of the In-Line Monitor design, results from initial on-site testing, and a description of the concentration calibration process.

INTRODUCTION

At the Fernald Environmental Management Project outside Cincinnati, Ohio (operated by the U.S. Department of Energy), a radioactive sludge waste comprised of uranium ore tailings has been removed from two silos and is being prepared for final disposal. The waste was generated at a uranium processing

plant that operated from the early 1950's to the late 1980's in the process of transforming raw ores into uranium cast billets. By mixing the sludge waste with water a liquid slurry is formed and eventually blended with fly ash and cement in order to create a disposable waste product. The activity of the final waste product is limited to amounts determined by regulatory limits for transport and for the final disposal site. The waste is known to contain radium, lead, and thorium as the primary radio-nuclides and is considered low-level radioactive waste. The activity in the final waste product is controlled by varying the mix of solid materials and water in the slurry, and to this end the radium concentration in the slurry must be monitored continuously. The monitoring system must therefore be able to provide accurate results on what amounts to a real-time basis.

Based on the design parameters provided by the end user, a transmission based in-line densitometer was adopted as the most suitable system for this application. Although there are several transmission based gamma-ray densitometry techniques and applications [1-6], the fundamental mathematical principle is the same. In this specific application, however, an adaptation to the standard algorithms and method was used. In the density determination a mixing rule is used relating the density of the dry solid material to the mass attenuation coefficient (MAC) of the slurry. The density obtained in this way is then incorporated with a self-attenuation correction factor (CF) based on the MAC's, and implemented in the concentration determination. Essential features of the design and algorithms for the In-Line Monitor (ILM) are described in the ensuing sections.

SYSTEM DESIGN

The measurement of the slurry takes place while it is in a re-circulation loop flowing through a "schedule-80" steel pipe having a ~50 mm (~2") diameter and a 5.54 mm wall thickness. The ILM system is designed to envelop the pipe but not be in

contact so that vibrations will not have an impact on the energy resolution of the detector. The maximum concentration in the solid dry waste product is expected to be 33 kBq.g⁻¹ (~900 nCi.g⁻¹), with an expected weight fraction of 20% to 50% in the slurry mixture. This gives a maximum expected concentration in the slurry of 16.5 kBq.g⁻¹ (445 nCi.g⁻¹). The design goal of the system is to measure ²²⁶Ra concentration over a 10:1 dynamic range with a standard deviation of ±10% or better. Based on a nominal chemical composition of the slurry provided by the end user, and based on sampling, the expected range of densities for the slurry is estimated to be 1.15 g.cm⁻³ to 1.50 g.cm⁻³.

The determination of the ²²⁶Ra concentration in the slurry is based on the detection of the 186 keV photon emitted by ²²⁶Ra. Secular equilibrium between ²²⁶Ra and its daughters could not be guaranteed, so direct determination was favored. The observed 186 keV intensity is corrected for attenuation in the slurry using a transmission measurement. The 122 keV γ emission from ⁵⁷Co was chosen for transmission primarily so that the Compton continuum from the transmission peak did not affect the determination of the 186 keV count rate. The choice of activity for the transmission source was based on achieving a statistically significant count rate after accounting for the attenuation through the slurry and the pipe. In order to prevent the life span of the system from being limited by the relatively short half life of ⁵⁷Co (~270 days), a removable Sn filter was designed into the source holder and an initial activity in excess of the desired amount was used. A source plug reduces the external dose to negligible levels.

A high purity germanium detector was chosen for the system with a high efficiency and superior resolution at the energies of interest. This meant having a sufficiently large front surface area, and a thickness that maximized the absorption of the ²²⁶Ra and ⁵⁷Co photons at 186 keV and 122 keV respectively, but minimized the event rate and energy deposition rate from the higher energy gamma emitters present in the slurry. The high resolution further enhances the signal-to-noise ratio by allowing the selection of a smaller region of interest around the peaks of interest. A shield was designed for the system in order to reduce the count rate from external sources of the slurry; there are three re-circulation loops (monitored by three ILM's) in the same area, and large slurry feed tanks in a neighboring room. High count rates from the slurry itself while being monitored contribute not only to the continuum background, but also to the signal of interest and a trade-off is thus made in the shielding design. An undesirable consequence, however, is a potentially high count rate and hence rate loss in the system. In order to account for this scenario interchangeable collimators were supplied with the system. Figure 1 contains different views of the ILM system. The top panel is a demonstration of the system in the factory with a schedule-80 pipe being assayed. The middle panel shows the system with the pipe access shield open. The bottom panel shows the ILM system installed in-situ at the final site. A complete description of the design guidelines for the system is given in [7].

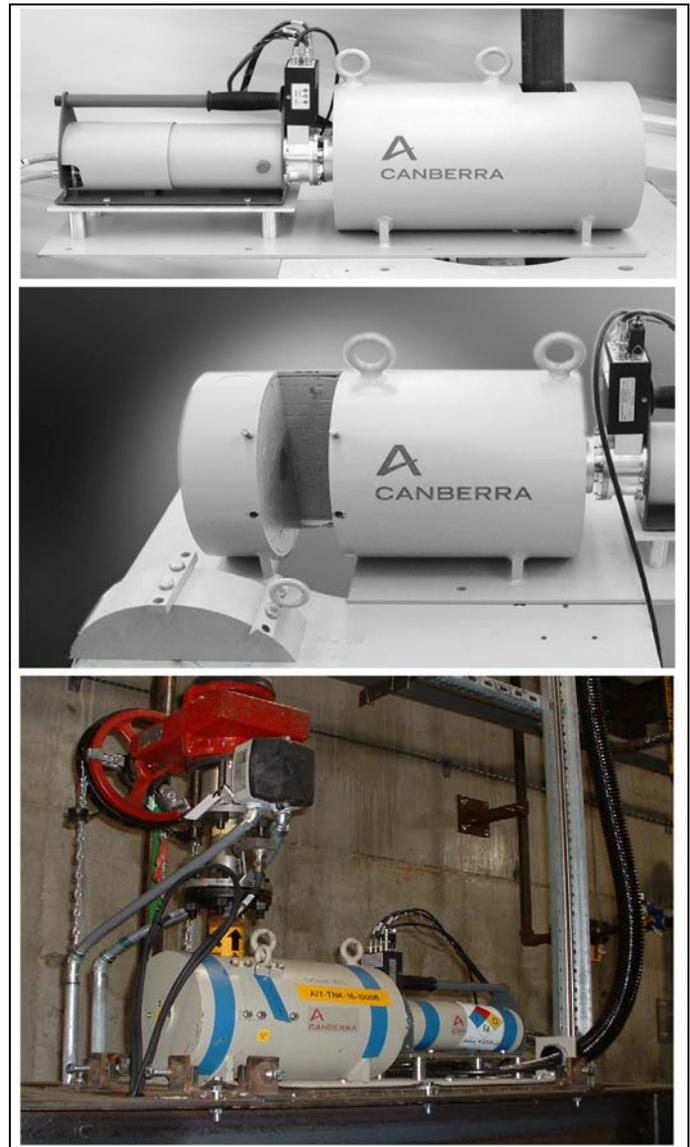


Figure 1. Views of the ILM system. Top panel: display of system in factory with schedule-80 pipe being assayed. Middle panel: system with pipe access shield open. Bottom panel: system installed on site showing shield, HPGe detector, preamplifier, electrical cabling and the hosing for the cryoelectric refrigerant.

SUMMARY OF ALGORITHMS

The development of the algorithms begins with the transmission equation

$$T = e^{-(\mu_p \rho) d_{eff}} \quad (1)$$

where T is the transmission, ρ is the density of the absorber, μ_p is the mass attenuation coefficient of the absorber, and d_{eff} is an effective thickness which is used in place of the nominal thickness of the absorber when required by geometrical considerations. The transmission “T” is the ratio I/I₀ where I₀ is the measured intensity of the transmission source determined from an empty pipe measurement, and I is the intensity when

the pipe contains the slurry. To determine the density of the slurry using the transmission measurement, Eq. (1) must be modified to take into account the variable mix of solid material and water in the slurry at any given moment.

If we denote the weight fraction of the solid material in the slurry by ‘w’ (relative to 1), the MAC of the slurry can be written as

$$\mu_{\rho,slurry} = w\mu_{\rho,sol.} + (1-w)\mu_{\rho,wat.} \quad (2)$$

where $\mu_{\rho,sol.}$ is the MAC of the solid material, $\mu_{\rho,wat.}$ is the MAC for water, and a simple binary mixture is assumed for the slurry. For the density of the slurry the following relationship is introduced:

$$\rho = \frac{1}{1-rw} \quad (3)$$

By setting $w=0$ in Eq. (3) (i.e. no solid material in the mix), $\rho(w=0) = 1 = \rho_{wat.}$ as required for the water density $\rho_{wat.}$. By setting $w=1$ in Eq. (3) the term ‘r’ becomes

$$r = 1 - \frac{1}{\rho_{sol.}} \quad (4)$$

where $\rho_{sol.}$ is the density of the solid material. By allowing $\rho_{sol.}$ to be a user-defined parameter, Eq. (3) permits some flexibility through use of the parameter ‘r’.

Eliminating ‘w’ between Eqs. (2) and (3), and substituting for $\mu_{\rho,slurry}$ using Eq. (1) gives the following expression for the density of the slurry:

$$\rho = \frac{(\mu_{\rho,sol.} - \mu_{\rho,wat.}) + r \ln(1/T) / d_{eff}}{\mu_{\rho,sol.} - \mu_{\rho,wat.}(1-r)} \quad (5)$$

Substituting for ‘r’ using Eq. (4) and defining the following terms

$$b = \frac{\rho_{sol.} - 1}{\rho_{sol.}\mu_{\rho,sol.} - \mu_{\rho,wat.}} \quad (6)$$

$$a = 1 - b\mu_{\rho,wat.} \quad (7)$$

$$c = \frac{b}{d_{eff}} \quad (8)$$

gives the final expression for the slurry density

$$\rho = a + c \ln(1/T) \quad (9)$$

where ‘a’ and ‘c’ are to be treated as empirical calibration constants and are determined by measurement with representative samples or by numerical calibration. Knowledge of the values for $\rho_{sol.}$, $\mu_{\rho,sol.}$, and an evaluation of d_{eff} thus become unnecessary as they are absorbed into the calibration constants. The advantage of having the expressions in Eqs. (6), (7), and (8), is that in the event that calibration measurements are not feasible, the constants ‘a’ and ‘c’ can be estimated to first order with an approximate knowledge of the composition of the solid material and measurement geometry. An additional advantage is that when both methods are available some cross checking is possible.

The radium concentration in the slurry is determined by the observed net count rate of the 186 keV γ emission. The expression for the concentration ‘C’ (in nCi.g⁻¹) is given by

$$C = \frac{R}{(V\varepsilon)} \frac{CF}{\rho} \quad (10)$$

where ‘R’ is the full-energy-peak count rate in counts/s, ρ is the slurry density (units of g.cm⁻³), ‘V’ is the volume of slurry in the field of view of the detector (units of cm³), ε is the detector efficiency for the measurement geometry (counts.s⁻¹.nCi⁻¹), and ‘CF’ is a dimensionless correction factor for attenuation. With the appropriate branching ratio for the 186 keV γ emission and Bq to nCi conversion, the concentration is expressed in units of nCi.g⁻¹. The choice of units for the concentration was determined by the end user requirements.

For the correction factor ‘CF’ the Parker [8] formula is adopted;

$$CF = \frac{\ln(1/T_2^k)}{1-T_2^k} \quad (11)$$

here ‘k’ is a calibration factor that accounts for geometrical effects in the system and T_2 is the transmission through the slurry in the pipe diameter at the *assay* energy 186 keV. The subscript in ‘ T_2 ’ is used to differentiate from the transmission measurement with the transmission source at 122 keV (T_1), though both can be related through the MAC’s for the slurry at the two different energies. By recognizing that ‘CF’ and ρ are functions of transmission, Equation (10) can be rewritten as

$$C = m \cdot R \cdot h(T) \quad (12)$$

where

$$h(T) = \frac{CF(T_2)}{\rho(T_1)} \quad (13)$$

and ‘m’ is a constant to be determined through calibration. As in the case with the density, in the absence of a calibration measurement the constant term in Eq. (12) can be estimated provided the efficiency term ‘ ε ’ in Eq. (10) can be calculated either analytically or using a detector efficiency model such as ISOCS [9]. With the calibration constant ‘m’ evaluated Eq. (12) serves as the expression by which the radium concentration in the slurry is determined.

A comprehensive description of the algorithm development can be found in [7]. In addition to the steps presented here, [7] includes full details of the density and concentration uncertainty calculations as well as the evaluation of the calibration parameters.

PRELIMINARY TESTS

Once the ILM’s were installed at the site, preliminary tests were performed using a surrogate material in place of the slurry. The surrogate material was non-radioactive so only the density functionality of the ILM could be tested. This test is important because the ILM measures the density as an intermediate step in producing the concentration result, and because it provides a valuable independent confirmation of the density value given by alternative density measuring instruments. One such instrument is a microwave densitometer (MWD) installed in series with the ILM and physically located just above it on the same section of pipe. Just as the ILM results are dependent (albeit minimally) on the estimated chemical composition of the dry solid material and the use of the mixing rule, the MWD results are likely susceptible to changes in the particulate size in the slurry as well as the

conductivity of the slurry. The density result from the ILM, though of secondary importance to the concentration result, is thus a useful by-product since the ILM can serve as an independent densitometer.

First the ILM was calibrated by performing a series of measurements with the surrogate material at various densities. The density of the surrogate material was varied by adjusting the water content in the mix as would be the case with the real slurry. During each calibration measurement a physical sample was taken and the density was determined using a dry solids laboratory analysis on site. This procedure was also used to calibrate the MWD simultaneously. Each density value determined via the laboratory analysis is associated with the transmission measured using the ILM and the resulting calibration data for the ILM are shown in Fig. 2.

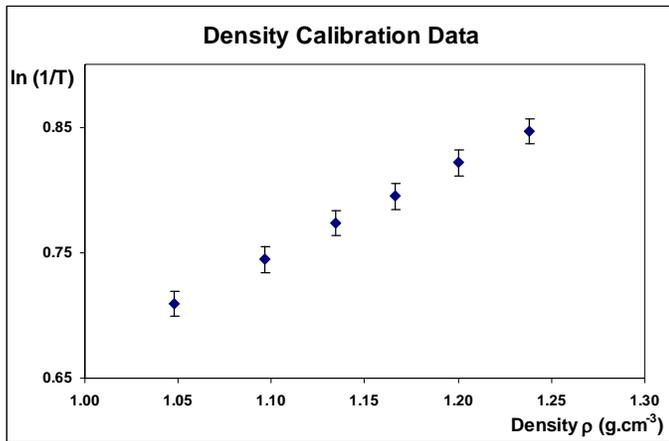


Figure 2. Density (ρ)-Transmission (T) plot for the calibration data.

In Fig. 2 uncertainties in the ordinate arise from counting statistics in the attenuated and unattenuated transmission source peak and were calculated by the system software. Uncertainties in the abscissa arise from the laboratory analysis in the weighing of the sample to obtain a solid weight fraction and the use of the mixing rule (Eq. (3)) in obtaining a slurry density where a dry solid density value must be assigned. These systematic uncertainty values were not available. The calibration parameters “a” and “c” (as in Eq. (9)) were obtained from the data shown in Fig. 2.

With the calibration in place the ILM was put into operational mode so that the system could be tested against a subsequent measurement with the surrogate material at yet another density. Since the software is designed to calculate rolling averages for the density and concentration results, the operator is able to choose the number of cycles to be used in the rolling average as well as the duration of each cycle. The density rolling average is given by:

$$\rho = \frac{\sum_k \rho_k / \sigma_{\rho_k}^2}{\sum_k 1 / \sigma_{\rho_k}^2} \quad (14)$$

where ρ_k and σ_{ρ_k} are the measured density and associated uncertainty for the “kth” cycle, with a sum taken over the

desired number of cycles. The uncertainty in the density rolling average is given by:

$$\sigma_\rho = \sqrt{\frac{1}{\sum_k 1 / \sigma_{\rho_k}^2}} \quad (15)$$

(Expressions for the rolling averages of the concentration and uncertainty are identical to Eqs. (14) and (15), with occurrences of ρ and σ_ρ replaced by C and σ_C respectively.)

Density values from the ILM are reported in several ways. The rolling average value and the associated uncertainty are displayed in real time on screen and are also output through a 4-20 mA card so that the values can be imported into other process controllers. In addition both the rolling average and instantaneous values are printed to a text report which is stored on disk and can also be sent directly to a printer. As a preliminary test of the calibration the density results from the ILM were compared with the results from the microwave densitometer (MWD) over the same time period and are shown in Fig. 3.

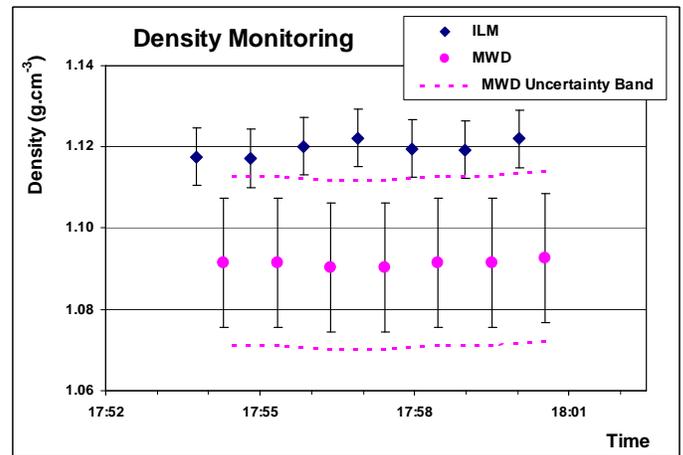


Figure 3. Reported densities and uncertainties at one standard deviation from the In-Line Monitor (ILM) and the Microwave Densitometer (MWD) in one-minute intervals. Diamonds: ILM values; Circles: MWD values; Dashed Lines: MWD uncertainty band.

The ILM density values in Fig. 3 (diamonds) were taken from the text report files and each data point represents the rolling average density based on the preceding five one-minute cycles. The uncertainties in the ILM values, calculated as in Eq. (15), are at the 1% level. The MWD values in Fig. 3 (circles) were read off from the time history of a process variable display screen. The MWD in essence measures the solid weight percentage in the slurry, from which the density of the slurry is obtained using the mixing rule described in Eqs. (3) and (4). A solid density of 3.0 g.cm⁻³ was assumed. Uncertainties in the MWD values are expected to be no better than 2% absolute on the measured solid weight percentage in the surrogate mix. For a solid weight percentage of 50% therefore the best possible *relative* error would be 4%, whereas for a solid weight percentage of 10% the *relative* error could be as high as 20%. The 2% absolute uncertainty was assigned to the MWD data and propagated to the derived density value, and is reflected in the error bars shown in Fig. 3. Also shown in the

figure is an uncertainty band (dashed lines) for the possible range of MWD values when the assigned solid density spans 2.7 - 3.3 g.cm⁻³. The reported densities from both instruments were within 3% of each other. Agreement at this level allows for the ILM to be used to track any sudden deviations in the MWD and vice versa.

CONCENTRATION CALIBRATION

For the concentration calibration of the ILM an independent means of determining the concentration must be available. Ideally a chemical analysis would be performed on a physical sample for each calibration data point, but this would require sending the samples off site which introduces the inconvenience of a time delay in creating the calibration. Such a method would be particularly cumbersome if for some reason the calibration measurements had to be repeated at some point during real-time operations where a delay of days would not be acceptable. An alternative approach using ²²⁶Ra calibration standards in a laboratory assay procedure was thus adopted and is described in this section. The use of a calibration standard establishes a relationship between a known activity and a measured count rate in the laboratory which can then be used to identify the activity of other samples.

During the recirculation process a physical sample of the mix in the pipe can be extracted in 25 ml increments and is captured in a sample jar. (The sample size can thus be any multiple of 25 ml.) The concentration calibration standards were therefore chosen to have the geometry of a 25 ml sample contained in a representative sample jar. The ²²⁶Ra activity is contained in an epoxy matrix situated in the bottom of the jar and different standards were obtained differing in the density of the epoxy matrix. Three calibration standards were used of densities 1.15, 1.50, and 1.70 g.cm⁻³ respectively, and were chosen to span the expected range of densities in the slurry. Each standard was assayed in a reproducible geometry using a gamma spectroscopy system. Using the known activity of the ²²⁶Ra calibration standard and the measured count rate of the 186 keV emission peak, the detection efficiency for the measurement geometry at 186 keV was determined. By measuring standards of different densities an efficiency curve was obtained as a function of density. This efficiency-density curve then served as the concentration calibration from which the ²²⁶Ra concentration for a sample of the slurry can be determined. (In this scheme the choice of activity for the ²²⁶Ra calibration standards is not important as long as good counting statistics can be achieved in a reasonable count time.)

Ascertaining the concentration of the slurry begins with measuring a 25 ml sample using the same gamma spectroscopy system in the identical geometry, and recording the count rate for the 186 keV peak. Next, the density of the slurry is determined by dry solids analysis. (The ILM density result can be used if the instrument has already been density calibrated, but generally both density and concentration calibrations will be performed simultaneously.) Once the density is known the efficiency-density curve is used to obtain an efficiency which together with the 186 keV count rate gives the ²²⁶Ra concentration.

While this method has the advantage of a rapid result, one drawback is that the efficiency determination does not take into account the attenuating effects of the high-Z (high atomic number) constituents of the actual slurry. The calibration standards though different in density, are all made of the same epoxy material which unlike the slurry has no high-Z constituents. The efficiency used in the concentration determination is thus most likely overestimated, and so the concentration most likely underestimated with an increasing effect at higher densities. To study the magnitude of this effect an ISOCS [9] simulation of the concentration calibration measurements was conducted using a detector description similar in size and characteristics to that used in the actual measurements. The measurement geometry including the description of the sample jar was reproduced as accurately as possible. For modeling purposes the composition of the epoxy by weight percentage was taken to be: H:6.00%, C:72%, O:22%. For the solid material in the slurry a nominal chemical composition was provided by the end user; constituents and their approximate weight percentages were SiO₂:62%, PbO:14%, BaO:7%, SO₃:4%, CO₂:4%, AL₂O₃:3%, Fe₂O₃:3%, Na₂O:2%, and MgO:1%.

Epoxy standards were defined at various densities beginning at 1.05 g.cm⁻³ with six increments in steps of 0.10 g.cm⁻³, and the additional densities of 1.50, and 1.70 g.cm⁻³ so that there was a data point at each of the three densities of the calibration standards. The result of the ISOCS simulation in each case is an efficiency value, so that an efficiency-density curve is generated. The simulation of the slurry material was done for slurry mixtures containing different weight percentages of the solid material mixed with water. The range of expected weight fractions of the solid material (20% to 50%) gives rise to a density span of 1.15 g.cm⁻³ (at 20%) to 1.49 g.cm⁻³ (at 50%). The simulation was performed for weight fractions in the range 20-50% in 5% increments. Figure 4 shows the results of the simulations compared with the measured calibration standards. In Fig. 4 the triangles indicate the measured efficiencies using the three epoxy calibration standards. The uncertainties were derived from counting statistics and the certificate systematic uncertainty in the activity values of the standards. Both a linear fit and a quadratic fit are shown on the plot, although the result of the ISOCS simulation indicates that the trend is linear. The diamonds indicate the efficiencies from the ISOCS simulation of the epoxy calibration standards, and the circles indicate the efficiencies from the ISOCS simulation of the slurry samples, with linear fits shown for both sets of data points. The dashed lines indicate the uncertainty band for the efficiencies from the ISOCS simulation of the slurry samples, where a systematic uncertainty of 10% is assigned to account for uncertainties in the detector dimensions and other measurement geometry uncertainties.

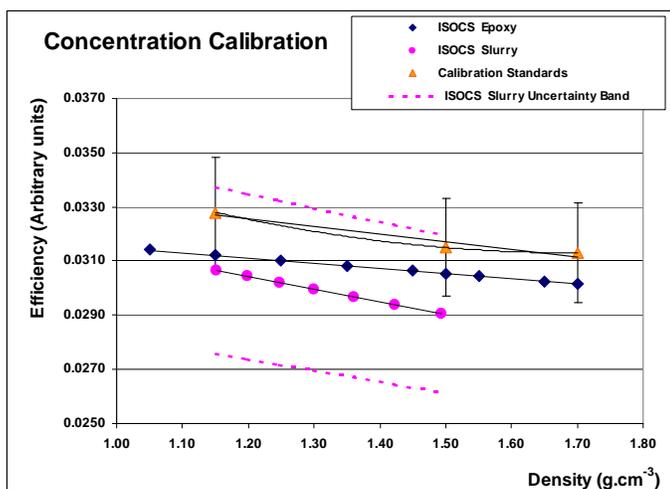


Figure 4. Comparison of efficiency-density relation for measured calibration standards and ISOCS simulations. Triangles: Calibration standards; Diamonds: ISOCS simulation of epoxy standards; Circles: ISOCS simulation of slurry samples; Dashed Lines: Uncertainty band for ISOCS simulation of slurry samples.

Table I is a comparison of the ISOCS simulations with the calibration standards.

Density ($\text{g}\cdot\text{cm}^{-3}$)	1.15	1.50	1.70
Calibration Standard efficiency	0.0328	0.0315	0.0313
Linear fit; efficiency deviation.	-0.06%	0.95%	-0.19%
ISOCS-Epoxy; efficiency deviation.	-4.83%	-3.02%	-3.61%
ISOCS-Slurry; efficiency deviation.	-6.42%	-7.78%	-10.19%

Table I. Efficiency comparison of ISOCS simulations with the calibration standard. Also given is a comparison of the efficiency values derived from a linear fit to the calibration values.

As seen in Table I the efficiencies from the ISOCS simulation of the *epoxy* calibration standards are within 5% of the actual calibration values (the negative sign indicates that the ISOCS values are smaller than the calibration values). While the level of agreement is very good given the possible systematic uncertainties, what is more important is that the trend is well reproduced. The efficiencies from the ISOCS simulation of the *slurry* samples show a deviation of 6-10% from the actual calibration values; the deviation increases with density as expected. Also shown are the deviations that result from fitting the calibration values with a linear function; these deviations are of the order of 1%.

Since the epoxy simulation accurately reproduces the density trend of the actual calibration standards, it can be used as a baseline for predicting the expected deviation in the concentration determination of the slurry samples. Comparing the last two rows in Table I it is apparent that deviations of 2-7% may be expected as a function of increasing density. Based on the result of this study two courses of action are available

during the concentration calibration of the ILM's. One is to adjust the concentration values obtained from the sample measurements using a density dependent scale factor obtained from the ISOCS simulations. (A similar adjustment would then also be necessary during subsequent verification measurements.) The other is to incorporate the density dependent deviation into the overall systematic uncertainties obtained during the calibration measurements. In this case some allowance must also be made for variations in the chemical composition of the slurry. At the time of writing no decision has been made on which method is preferred by the site.

PRELIMINARY MEASUREMENTS

Once the basic functionality of the ILM system had been verified with the non-radioactive surrogate material, the systems were deemed ready for use with the actual slurry. The radioactive slurry material was introduced into the three separate re-circulation loops and preliminary calibration and verification measurements were performed for the three ILM systems.

Each system was calibrated with a simple two-point calibration. One of the calibration measurements was made with clean water flowing in the pipe so that the density and concentration values were known *a priori*. The other calibration measurement was made with the slurry in re-circulation and the density and ^{226}Ra concentration were ascertained by sample analysis in the laboratory as described previously. Once the calibrations were in place a verification measurement was made for each system where a sample of the slurry was taken and the results of the laboratory analysis were compared with the ILM reading at the time the sample was extracted. The density results for the three ILM systems are shown in Table II while the concentration results are shown in Table III.

	Lab density ($\text{g}\cdot\text{cm}^{-3}$)	ILM density ($\text{g}\cdot\text{cm}^{-3}$)	Deviation (%)
System A	1.323 ± 0.023	1.319 ± 0.007	0.29
System B	1.282 ± 0.022	1.304 ± 0.005	-1.67
System C	1.259 ± 0.021	1.227 ± 0.006	2.54

Table II. Density verification measurement results for ILM systems.

	Lab concentration ($\text{nCi}\cdot\text{g}^{-1}$)	ILM concentration ($\text{nCi}\cdot\text{g}^{-1}$)	Deviation (%)
System A	74.41 ± 9.93	82.97 ± 0.92	-11.51
System B	84.51 ± 10.65	76.59 ± 0.90	9.38
System C	74.34 ± 9.38	62.54 ± 0.84	15.87

Table III. Concentration verification measurement results for ILM systems.

The density results are in excellent agreement with deviations of less than 3%. The concentration results show larger deviations, but the uncertainties in the laboratory values

themselves are quite large. In addition systematic uncertainties arising from the epoxy-slurry material discrepancy are not reflected in the uncertainties given in Table IV. The ILM and laboratory concentration results as a function of the laboratory density are shown in Fig. 5.

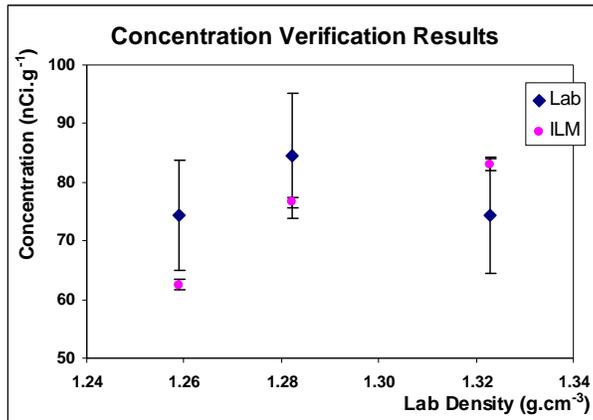


Figure 5. Concentration verification measurement results for ILM systems, as a function of laboratory density.

CONCLUSION

This paper describes the use of an In-Line Monitor system for the direct measurement of the ²²⁶Ra concentration in a slurry. The system is based on a transmission measurement using the 122 keV γ from ⁵⁷Co to obtain the slurry density, and quantitative gamma-ray spectrometry applied to the 186 keV γ emission in order to determine the concentration. The density information and a self-attenuation correction factor determined from the transmission measurement are both incorporated in the concentration determination. Near real-time rolling average results are presented to the operators allowing control of the mixing of the final waste product as well as providing constant monitoring. In comparison sampling data is slow and may not be representative. The approach can be applied to other nuclides besides ²²⁶Ra, and in fact the system reports the concentration of ²¹⁴Pb as well based on the 352 keV γ line. The system has been installed at the final operational site where preliminary measurements have been made with the slurry. The initial measurements demonstrate the successful operation of the system in reporting density and concentration results. In addition a study of the concentration calibration method has been conducted in order to quantify the systematic uncertainties in the concentration values. At the time of writing preliminary site operations have commenced based on the performance of the In-Line Monitor systems and further results are expected in the near future.

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