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30 August 2010

Energy Fuels Resources Corporation
44 Union Boulevard, Suite 600
Lakewood, CO 80128

Attention: Frank Filas, P.E., Environmental Manager

Re: Evaporation Pond Radon Flux Analysis, Piñon Ridge Mill Project, Montrose County, Colorado

Dear Frank,

This letter is to address Task 1 of our proposal of 16 June 2010 relative to radon flux from evaporation ponds, namely:

- Task 1: Estimate the radon flux from the proposed Piñon Ridge Mill evaporation ponds for both an initial 40 acres of ponds and a potential increase to 80 acres. In addition, the effect of spraying to enhance evaporation has been considered.

Task 1 is directed towards providing information to the U.S. Environmental Protection Agency (EPA) relative to their current Subpart W NESHAP rulemaking. We understand that this information will be provided as a courtesy to the EPA since Energy Fuels does not believe that the ponds are within EPA's regulatory mandate.

As shown below, using a model from Nielson and Rogers for water-covered uranium tailings, [whose work has been the primary basis for NRC and EPA radon emission models from uranium tailings impoundments], it can be shown that the radon flux from the evaporation ponds at the Piñon Ridge Mill site is expected to be well within the range of pre-operational background radon flux rates measured at the proposed tailings locations. The basis for this conclusion is presented in subsequent sections of this letter.

We would be pleased to answer any questions you may have concerning our evaluation. In my absence, please communicate with my colleague Dr. Douglas Chambers.

Yours very truly,

For SENES Consultants Limited

Steven H. Brown, CHP

cc: Dr. Douglas Chambers, dchambers@senes.ca

ATTACHMENT

1.0 INTRODUCTION

1.1 Background

Energy Fuels Resources Corporation (EFRC) is in the process of completing designs for a uranium mill, termed the Piñon Ridge Project, located in Montrose County, Colorado. The mill is designed for start-up operations at 500 tons per day (tpd) (Phase I), with a potential to expand to 1,000 tpd (Phase II). The design raffinate flows from the process circuit are in excess of that needed for re-circulation to the mill; therefore, the design of the mill requires construction of 10 evaporation ponds (Phase I) and another 10 evaporation ponds (Phase II) for the disposal of the excess raffinate solution from the milling operation. The evaporation ponds are expected to be very small sources of radon emissions to the ambient air. To confirm this assumption, and in the interest of demonstrating that radon emissions to unrestricted areas from operation of the Piñon Ridge Mill will be maintained ALARA, these potential radon emissions are the subject of this assessment.

The emission of radon from uranium tailings has been studied and modeled for many years. For example, the U.S. Nuclear Regulatory Commission (NRC) makes use of their 1984 handbook for uranium tailings cover design (Rogers et al. 1984).

Because of the very low diffusion of radon through water (as compared to partially air-filled unsaturated tailings pores), the diffusion of radon through water-covered tailings has been argued to be effectively zero (e.g. Chambers 2009). The EPA has previously assumed zero radon emissions from ponded areas of uranium tailings impoundments (e.g. EPA 1986). This is based on the assumption of no or low measurable radium concentrations in water covering the tailings; that is, the source of radon-222 (radon) is primarily the radon from the radium-226 (Ra-226) in the tailings. However, during a recent presentation at the annual National Mining Association /Nuclear Regulatory Commission (NMA/NRC) Uranium Workshop in Denver, Colorado, representatives of the United States Environmental Protection Agency (EPA) stated that the work practice standards in its 40 CFR Part 61, Subpart W *National Emissions Standards for Radon Emissions from Operating Mill Tailings* apply to evaporation ponds at conventional and in situ uranium recovery (ISR) sites licensed by NRC or its Agreement States.

A presentation by Baker and Cox (2010) at the most recent NMA/NRC workshop in Denver considers the situation where appreciable concentrations of radon are present in the ponded water, as may arise for example from elevated levels of Ra-226 dissolved in the pond water. Baker and Cox, reporting on a stagnant film model and some measurement data, suggest a radon flux of the order of 1 pCi m^{-2} s^{-1} per 100 pCi/L of dissolved radon in the ponded water.

1.2 Published Models and Regulatory Context

As previously noted, much of the work on radon emission models undertaken by Rogers and Associates has been adopted by the U.S. NRC and is widely used by the NRC and others in assessing radon releases from uranium tailings. Besides the NRC use of the Rogers et al models in the NRC 1984 handbook for uranium tailings cover design (Rogers et al 1984), their work is also the basis for NRC's Regulatory Guide 3.64 on radon attenuation by earthen tailings covers (NRC 1989).

In some earlier work, Nielson and Rogers (1986) examined the issue of surface water considerations in predicting radon emissions from water-covered uranium tailings impoundments. They suggest that radon emissions from water-covered tailings can be non-zero. These authors attribute this to advective mixing, as opposed to straight radon diffusion mechanisms. Although there are various papers on the diffusion and transport of radon available from published literature, the 1986 work of Rogers and Nielson is of direct relevance to the present study of radon emissions from evaporation ponds, and was adopted for application here.

The Nielson and Rogers model (1986) makes use of equations based on the well-known first Fick's Law of gaseous diffusion (non-reactive) through media in order to estimate surface radon flux rates. They considered that mixing leading to non-diffusive radon emissions could take place in the top 1 m of water cover within tailings impoundments. In their analysis, they divided radon releases into three components:

- radon originating from tailings covered with < 1 m of water;
- radon originating from tailings covered with > 1 m of water; and
- radon originating from dissolved radium in the pond water.

In this approach used by Nielson and Rogers, the emission of radon from shallow waters is controlled by the emanation of radon and diffusion through the pore water. However, the radon emission from tailings covered with deep water (>1 m) is controlled by the diffusion of radon through the water column. As noted further below, the assumption of complete release in the top 1 m is conservative in that the mixing advective layer would likely be less than 1 m deep.

Regulatory Context

It is beyond the scope of this analysis to comment on the applicability of the Subpart W NESHAP limits on radon emissions from operating mill tailings (EPA 1989), other than to note that the applicability of the rule to evaporation ponds has been questioned. For present purposes, to provide a context for the estimates of radon flux described below, a reference value of 20 pCi m^{-2} s^{-1} has been assumed for uranium tailings impoundments. This flux rate, which represents the regulatory limit in Subpart W for tailings impoundments constructed prior to December 1989, was typical of tailings impoundments operating in the 1980s.

The baseline radon flux for the site represents a second point of reference. The Piñon Ridge site has been used historically for grazing cattle and has not been impacted by uranium mining or milling activities. Radon emission rates were measured at nine locations within the proposed tailings areas on three separate occasions (fall, spring, and summer). The radon-measuring canisters were analyzed using EPA Test Method 115, Monitoring for Radon-222 Emissions. The background radon flux rates ranged from 0.41 to 3.78 pCi m^{-2} s^{-1} and averaged 1.7 pCi m^{-2} s^{-1} (ERG 2009).

1.3 Approach to the Present Problem

In this study, we examined the effect of various wind speeds on the radon emission rates from the evaporation ponds based on the Nielson and Rogers model. In order to improve performance of the evaporation pond system (i.e., enhance the evaporative capabilities), the design of the ponds includes implementation of a sprinkler system. The sprinklers will be placed and sized to maximize evaporation and minimize the potential for wind drift beyond the extent of the lined evaporation pond area. In this assessment, the emission of radon from sprinkler systems was also estimated.

While the Nielson and Rogers model can theoretically be used for estimation of radon emissions from the evaporation ponds, the following potential limitations should be noted. The tailings are relatively thick and a significant radon concentration gradient may be developed across the thickness of the tailings due to diffusional movement of radon towards the solid-liquid interface. In the evaporation ponds, however, the precipitate layer may be much thinner and the concentration of radon in the pore water can be assumed to be uniform across the thickness of the precipitate layer.

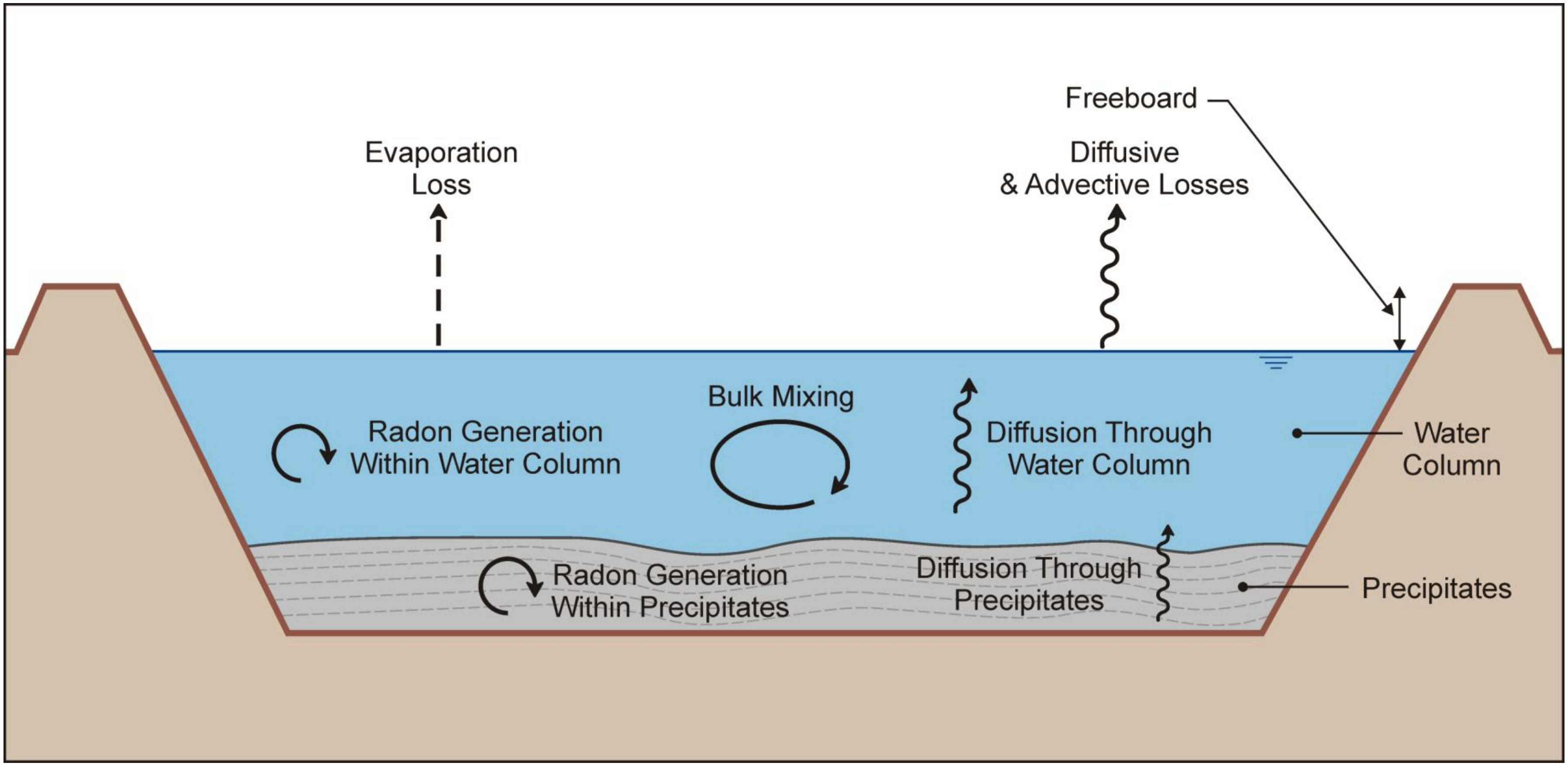
The Nielson and Rogers model provides a conservative estimate of radon emissions based on the assumption of complete mixing in the top 1 m layer of the water covering the tailings. Nielson and Rogers based their model on observed wave action at the air-water interface. On a smaller scale, such as over evaporation ponds, the magnitude of the wave dimensions may not be large enough to induce complete mixing in the top 1 m of the water column.

2.0 RADON EMISSION MECHANISMS

2.1 Overview of Radon Emanation Mechanisms

Radon occurs in raffinate and precipitates in the evaporation ponds naturally as the decay product of the dissolved radium in pond water and radium in the precipitates. Figure 1 shows various mechanisms involved in the release of radon from the evaporation ponds.

Figure 1: Mechanisms Involved in the Release of Radon from the Evaporation Ponds



Radon produced in water diffuses toward the direction of its decreasing concentration in water (in most cases toward the air-water interface where it is released to the ambient air). In stagnant water columns, the diffusion of radon can be described by Fick's Law, which states that the flux density of the diffusing radon is linearly proportional to its concentration gradient and its diffusion coefficient in water. In water columns, the diffusion of radon is enhanced by various mechanisms such as natural convection in the water column and wind action. As a result, the Fick's Law is expressed in term of effective diffusion coefficient. Typically, the gas transport across the air-water interface is expressed using the overall mass transfer coefficient. This coefficient is very sensitive to the thickness of the boundary layers in both sides of the interface and the wind speed over the water surface.

In addition to the above transfer mechanisms, the transport of radon produced inside the solid particles is also influenced by the diffusion of radon within the solid particle. After being generated, the radon atoms tend to move away from their original location toward the pore spaces in the medium. Consequently, depending on their original location within the solid phase, the pore distribution, and the moisture content of the solid particles, the newly created radon atoms may end up within the same solid particle in which they were created, or within the pore of the medium. Table 1 shows nominal diffusion coefficients for radon in water and in air as reported by Drago (1998).

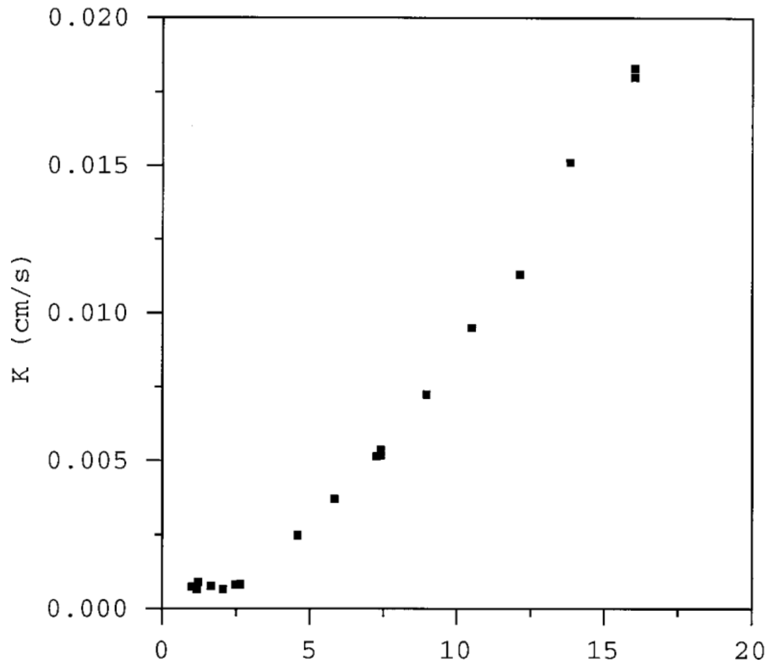
Table 1: Diffusion Coefficient of Radon in Water and Air at 20°C
Source: Drago (1998)

Medium	Value	Unit
water	1.2×10^{-5}	cm^2/s
air	0.12	cm^2/s

Since the diffusion coefficient of radon in air is approximately 10,000 times larger than its diffusion coefficient in water, the migration of radon in saturated solids is much different than its migration in unsaturated solids. The fraction of the total amount of radon produced by radium decay that escapes from the solids particles and gets into the pores of the medium is referred to as the radon emanation coefficient or emanation fraction (often written as E). The radon emanation coefficient is strongly influenced by the moisture content of the medium, particularly within the range of low water saturation.

A clear change in trend of the data, separating these two regimes, occurs at u=3 m/s as shown in Figure 2. Ocampo-Torres et al (1994) note that this critical wind speed corresponds to the lowest value of u at which waves are observed. In another study, Kanwisher (1963) observed a sudden increase in the rate of CO_2 outgassing in a wind/wave tunnel, at a wind velocity of about 3 m/s where the waves begin to emerge. It is suggested that the random surface drift velocities observed at the surface of water may act to generate some degree of bulk mixing.

Figure 2: Typical Plot of Mass Transfer Coefficient K versus Wind Speed in a Wind/Wave Tunnel. Source: Saylor and Handler (1997)



The wave dimensions versus wind speed depend on the geometry and size of the ponds and could not be easily established for this study. However based on the information available from the pond design documents regarding the depth of the freeboard (1 ft), it is expected that the maximum wave depth would be less than 1 ft for the maximum wind speed (18.1 miles/hour or 8.1 m/s) for the site[1]. The average wind speed for the site is considerably less at 6.2 miles/hour or 2.8 m/s. According to the above observations, no significant wave action is expected to occur at the surface of the ponds at the average wind speed.

3.0 PHYSICAL PARAMETERS

3.1 Description of Evaporation Ponds

The design flow rates of raffinate associated with the start-up (500 ton per day) and ultimate production rates (1,000 ton per day) are 63 and 126 gallons per minute (gpm), respectively. The average volumetric flow rate to the evaporation ponds for the 1,000 tpd scenario is somewhat less at 117 gpm (7.4 L/s) (Golder 2008). The evaporation pond system is designed for construction in two phases. Phase I includes 10 ponds (or cells), each with a surface dimension of 300 feet by 600 feet (i.e., 91 m by 182 m), designed to evaporate the inflows associated with the 500 tpd production schedule. Similarly, Phase II includes an additional 10 ponds with the

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[1] Maximum average daily wind speed recorded over 730-day period. From Pinon Ridge Meteorological Data Base maintained by Energy Fuels Resources Corporation (2010).

same dimensions designed to evaporate the flows associated with the 1,000 tpd production schedule Golder 2008).

Both phases of construction are designed with an additional one foot of freeboard (above the required design capacities). The water depth in each pond will be similar, maximizing the evaporative surface area. In order to improve performance of the evaporation pond system (i.e., enhance the evaporative capabilities), the design includes implementation of a sprinkler system. The sprinklers will be placed and sized to maximize evaporation and minimize the potential for wind-drift beyond the extents of the lined evaporation pond area.

3.2 Parameters Used for the Modeling

Table 2 shows the physical parameters used for the current evaluation. These parameters were compiled from data provided by Energy Fuels based on their current designs for the evaporation ponds (Golder 2008). In addition, Energy Fuels contracted with J.E. Litz and Associates to undertake bench-scale studies to characterize the raffinate (Energy Fuels 2010). Measurement data on radium concentrations in precipitate and pond water were available from the studies. Relative to the pond water, the measured radium concentrations ranged from 59 to 600 pCi/L, with an average of 241 pCi/L. For this analysis, the maximum value of 600 pCi/L was conservatively assumed.

Table 2: Physical Parameters Used for the Current Evaluation

Parameter	Value	Unit	Reference
Concentration of radium in precipitates	7.9	pCi/g	Energy Fuels (2010)
Concentration of radium in pond water	600	pCi/L	Energy Fuels (2010)
Ambient air radon concentration	270	pCi/m^3	Estimate*
Bulk density of precipitates	2	g/cm^3	Estimate
Radon emanation coefficient	0.35	-	Nielson and Rogers 1986
Radon decay constant	$2.1x10^{-6}$	1/s	Nielson and Rogers 1986
Radon diffusion coefficient in water	$1.2x10^{-5}$	cm^2/s	Drago 1998
Radon diffusion coefficient in air	0.12	cm^2/s	Drago 1998
Effective diffusion coefficient of radon in deep water**	0.003	cm^2/s	Nielson and Rogers 1986
Radon Henry's Constant	4.08	dimensionless	Drago 1998
Pond width	91	m	Golder 2008
Pond length	182	m	Golder 2008
Number of ponds	10 (P I) and 20 (PII)	-	Golder 2008
Total evaporation rate	117	GPM	Raffinate flow rate, Golder 2008
Average evaporation rate	$4.4x10^{-5}$	$L\ m^{-2}\ s^{-1}$	Estimated based on data in Golder 2008

* Based on a generic value in the order of 10 Bq/m^3 for background radon (UNSCEAR 2009, NCRP 2009).

** Effective diffusion coefficient incorporates the effect of natural convection and other mixing in water column on the diffusional transport of radon in water column toward the surface.

4.0 ESTIMATION OF THE RADON FLUX

4.1 Diffusive and Advective Radon Emission

Estimates based on Nielson and Rogers

The information in previous sections was used in the Nielson and Rogers (1986) model as implemented by SENES to estimate the radon emissions from the ponds at high surface turbulence conditions. This model considers both diffusion and turbulence at the air-surface interface by assuming that the radon in the top 1-m layer of water is released to air instantly. Table 3 shows the results of the emission estimation for two depth scenarios. The input and output values, as well as the equations used for calculations, are provided in Appendix A.

Table 3 summarizes the results (Appendix A) of the emission estimates for two water cover depth scenarios. For comparison purposes, the same parameters shown in Table 2 were used to estimate the radon emissions using the on-line program that is available from the World Information Services on Energy (WISE) website, also attributed to the Nielson and Rogers (1986) model. It is not known if or to what degree the on-line program has been independently verified; however, the program produced the same results as generated by the model and scenarios used in this assessment (see http://www.wise-uranium.org/ctb.html). [Appendix B provides details on the parameter values used in the calculations with the on-line model.] It should be noted that unlike the edges of tailings impoundments, the precipitates in the evaporation ponds would be covered by water (i.e., submerged) at all times.

Table 3: The Results of the Emission Estimation for Two Depth Scenarios

Depth Scenario	Radon Flux ($pCi\ m^{-2}\ s^{-1}$)	Total Radon Emission (Phase I) (pCi/s)	Total Radon Emission (Phase II) (pCi/s)
Water cover less than 1 m deep	0.91	$1.52x10^5$	$3.04x10^5$
Water cover 3 m deep	1.27	$2.12x10^5$	$4.24x10^5$

The results of calculations indicate that, for the current situation, as the depth of water increases, the radon emissions increase. According to the Neilson and Rogers model (1986), this is because the radium concentration in the water column becomes a major contributor of the total radon flux from the ponds.

As mentioned before, the results shown in Table 3 (based on the Neilson and Rogers model) represent highly turbulent surface conditions on the ponds. This will provide a conservative estimate of the emissions as in the majority of time, the surface of the ponds will be relatively calm and free of significant waves.

Effect of Wind speed

As shown on Figure 2 in Section 2.2, the mass transfer coefficient, K, is small and only weakly dependent on wind speed, u, when u is below 3 m/s. K is much larger and more sensitive to u at higher wind speeds.

Considering that the transfer rate at the air-water interface has a linear relationship with the mass transfer coefficient, the emission rate is expected to be much less at average wind speeds (6.2 miles/hour or 2.8 m/s) compared with the emission rates at the maximum average wind speed (18.1 miles/hour or 8.1 m/s) where waves of less than 1 ft (0.3 m) are expected to form at the surface of the ponds. Table 4 shows the effect of various wind speeds on radon emissions from the ponds. [The mass transfer coefficients (K) in Table 4 were estimated from Figure 2.] Appendix A provides additional details of the radon flux calculations.

Table 4: The Effect of Wind Speed on the Radon Flux*

Wind Speed, m/s	Mass Transfer Coefficient (K) (cm/s)	Radon Flux (pCi m^{-2} s^{-1})	
		Water Depth: 3 m	Water Depth: 1 m
8.1	0.0055	1.27	0.91
6.0	0.003	0.69	0.50
4.0	0.002	0.46	0.33
2.8	0.0014	0.32	0.23
2.4	0.001	0.23	0.17

*Sample calculation (3 m depth):

Maximum flux at maximum wind speed (8.1 m/s) = 1.27 pCi m^{-2} s^{-1} (at 3 m depth from Table 3)
Mass transfer coefficient at maximum wind speed = 0.0055 cm/s (Figure 2)
Mass transfer coefficient at 2.8 m/s wind speed = 0.0014 cm/s (estimated from Figure 2)
Radon flux at 2.8 m/s wind speed = 1.27 pCi m^{-2} s^{-1} * 0.0014 / 0.0055 = 0.32 pCi m^{-2} s^{-1} (assuming linearity)

4.2 Evaporative Radon Emission

Radon produced in the water column could be released to ambient air via evaporation. It is expected that the entire radon content dissolved in the portion of the water evaporated is released. As a thin film at the interface is being evaporated all the time, the concentration of radon in the water right at the interface can be estimated. This was done using the Henry's Law constant for radon and the concentration of radon in ambient air provided in Table 2. The concentration of radon at the interface was estimated at 1.1 pCi/L as shown below:

Ambient air radon concentration = 270 pCi/m^3 (Table 2)
Henry's constant for radon = 4.08 (Table 2)
Water activity concentration = Henry's constant * Air activity concentration =
4.08 * 270 pCi/m^3 = 1102 pCi/m^3 = 1.1 pCi/L

The evaporation rate of water was estimated using the average flow of raffinate to the ponds (117 gpm or 7.4 L/s) over the total surface area of the ponds ($1.67x10^5$ m^2) which is $4.4x10^{-5}$ L m^{-2} s^{-1}:

Evaporation rate = 7.4 L/s / ($1.67x10^5$ m^2) = $4.4x10^{-5}$ L m^{-2} s^{-1}.

The radon release was estimated as follows:

Radon release = Interface water concentration * Evaporation rate

= 1.1 pCi/L * $4.4x10^{-5}$ L/m^2/s = $4.9x10^{-5}$ pCi m^{-2} s^{-1}

This value is extremely insignificant compared to the diffusional release of radon.

4.3 Radon Emission from the sprinklers.

Rost (1981) demonstrated the ability of spray aeration to remove radon from well water at private homes in Maine. One-stage aeration system achieved 75.7% radon removal efficiency. It was assumed that the rate of removal of radon from sprinkler systems is similar to the removal rate of radon from spray aeration system used by Rost (1981).

The radium concentration in raffinate, the raffinate average flow rate, and the removal efficiency of sprinkler were used to estimate the radon release from the sprinkler systems. It was assumed that the sprayed water is in contact with air for 10 seconds and sprinklers are one-stage systems with the removal efficiency of 75%.

Evaporation rate = 117 gpm = 7.4 L/s
Radium concentration in water = 600 pCi/L (Table 2)
Total radium loading in 10 seconds = 7.4 L/s * 10 s * 600 pCi/L = 44,400 pCi
Radon production = Total radium * Radon decay constant =
44,400 pCi * $2.1x10^{-6}$ s^{-1} = 0.0.093 pCi/s
Radon release (75% efficiency) = 0.093 pCi/s * 0.75 = 0.07 pCi/s

The calculations indicate that the total radon emission is approximately 0.07 pCi/s for the sprinkler system. This value is extremely insignificant compared to the estimated value based on the Neilson and Rogers model (diffusion and wave action from the evaporation ponds).

5.0 ESTIMATION OF THE AIR CONCENTRATION

The method used to calculate the concentration of radon in the atmosphere over the evaporation ponds was based on the box model developed by Schiager (1974) to calculate the atmospheric radon concentrations near the uranium mill tailings piles. Assuming that 5 ponds were placed end to end, the following equation was used for calculations (Schiager 1974):

$$C_{Rn} = \Phi X / u\sigma_z$$

where:

C_{Rn} = radon concentration in atmosphere (pCi/m^3)

Φ = radon emission flux (0.32 pCi m^{-2} s^{-1} for the average wind speed of 2.8 m/s)

X = maximum length of the evaporation ponds in the direction of the wind (5 ponds * 182 = 910 m)

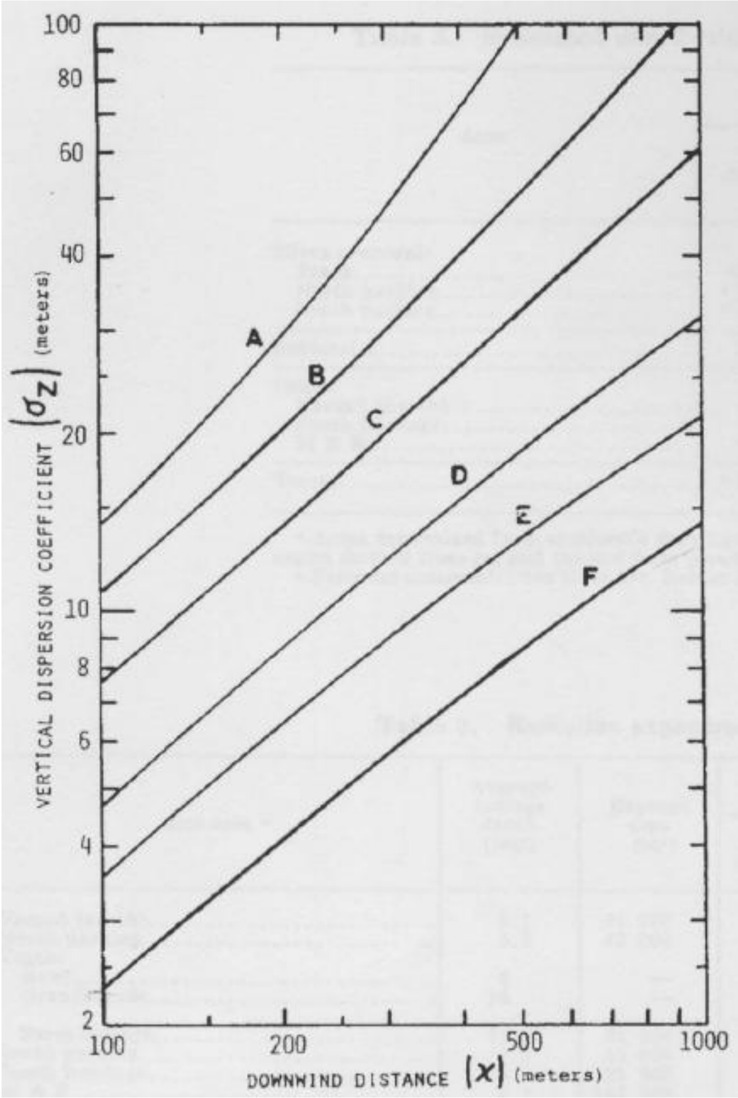
u = average wind speed (2.8 m/s)

σ_z = vertical dispersion coefficient (14 m from Figure 3 based on a conservative assumption of F stability class, i.e. the least atmospheric dispersion)

The resulting radon concentration is:

$$C_{Rn} = 0.32 \text{ pCi m}^{-2} \text{ s}^{-1} * 910 \text{ m} / (2.8 \text{ m/s} * 14 \text{ m}) = 7.4 \text{ pCi/m}^3$$

Figure 3: Vertical Dispersion Coefficient by Atmospheric Stability Class (Schiager 1974)



The above estimate of 7.4 pCi/m^3 is the incremental (above background) air concentration due to the emission of radon from the evaporation ponds. This value is very small (3%) compared to the assumed background atmospheric radon concentration of 270 pCi/m^3 (Table 2).

6.0 DISCUSSION AND CONCLUSION

Conservative estimates of radon flux indicates that the emissions are low and less than or similar to the pre-operational average background radon flux of 1.7 pCi m^{-2} s^{-1} observed at various locations within the proposed tailings areas on the site. The estimated radon flux levels from the evaporation ponds is also a small fraction (less than 10%) of the 20 pCi m^{-2} s^{-1} limit for pre-1989 uranium tailings that has been assumed here for context. This conservative estimate was based on the Nielson and Rogers model. The model assumes that the emission rates are enhanced by the turbulence at the top layer of the water column where all the radon in the top one-meter of water is assumed to be released to air instantaneously. For comparison purposes, the same parameters were used to estimate the radon emissions using an on-line program that is available on the World Information Services on Energy (WISE) website. The on-line model, which is attributed to the Rogers and Nielson model, produced identical results.

The results of this assessment also indicated that the radon emissions associated with the evaporation of the raffinate solution and the emissions due to the operation of sprinkler system are extremely low and insignificant compared to the radon flux from the ponds due to diffusional and turbulence processes.

Finally, the calculations indicated that the incremental air concentration due to the emission of radon from the evaporation ponds is very small (on the order of 3%) relative to the assumed background radon concentration.

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APPENDIX A: INPUT PARAMETERS FOR NIELSON AND ROGERS MODEL

The input parameters for Nielson and Rogers (1986) model for a 3 m deep water column:

Ra	tailings Ra content	7.9	pCi/g
Raw	Raffinate Ra content	0.6	pCi/cm3
dens	bulk density of tailings	2	g/cm3
E	Rn emanation coeff	0.35	-
lambda	Rn decay constant	2.1E-06	1/s
D	diff. coeff. in tailings	1.2E-05	cm2/s
Fs	fraction of pond with < 1 m depth	0	-
Dtr	eff. stagnant water transport coeff	0.003	cm2/s
Xp	avg. pond depth for areas > 1 m depth	250	cm

The output from Nielson and Rogers (1986) model for 3 m deep water column:

At	attenuation factor for deep water	1.89E-02	
J	Radon flux	1.27E+00	pCi m^{-2} s^{-1}

The input parameters for Nielson and Rogers (1986) model for a 1 m deep water column:

Ra	tailings Ra content	7.9	pCi/g
Raw	Raffinate Ra content	0.6	pCi/cm3
dens	bulk density of tailings	2	g/cm3
E	Rn emanation coeff	0.35	-
lambda	Rn decay constant	2.1E-06	1/s
D	diff. coeff. in tailings	1.2E-05	cm2/s
Fs	fraction of pond with < 1 m depth	1	-
Dtr	eff. stagnant water transport coeff	0.003	cm2/s
Xp	avg. pond depth for areas > 1 m depth	Not Applicable	cm

The output from the Nielson and Rogers (1986) model for a 1 m deep water column:

At	attenuation factor for deep water	1.89E-02	
J	Radon flux	9.08E-01	pCi m^{-2} s^{-1}

The following equation was used to calculate the attenuation factor (A_t):

$A_t = \exp[-\mathrm{sqrt}(\lambda/D_{tr}) * (X_p - 100)]$ (Nielson and Rogers 1986)

where:

λ = radon decay constant (2.1×10^{-6} s^{-1})
D_{tr} = effective diffusion coefficient in water column (cm^2/s)
X_p = average pond depth for areas greater than 1 meter deep (cm)

The following equation was used to calculate the radon flux (J) from the evaporation ponds:

$J = 10^4\, R\rho E * \mathrm{sqrt}(\lambda D)[f_S + (1-f_S)*A_t] + 10^6\, R_w \lambda S_d(1-0.5f_S)$ (Nielson and Rogers 1986)

where:

J = radon flux from the exposed pond surface (pCi m^{-2} s^{-1})
R = solids radium content (pCi/g)
R_w = water radium content (pCi/cm^3)
ρ = bulk solid density (g/cm^3)
E = radon emanation coefficient for solids (dimensionless)
D = radon diffusion coefficient in pore water (cm^2/s)
f_S = fraction of pond area with less than 1 m deep
S_d = depth of surface layer from which all radon is assumed to be released = 1 m

The 10^4 factor converts the flux units from pCi cm^{-2} s^{-1} to pCi m^{-2} s^{-1}. The 10^6 factor converts the water radium content (R_w) from units of pCi/cm^3 to pCi/m^3. For consistency of units, the S_d parameter, not explicitly shown in Nielson and Rogers (1986), was included here.

APPENDIX B: PARAMETER VALUES USED IN ON-LINE MODEL

Input Parameters: 3 m deep water column

Parameter	Parameter Values Used in On-Line Model	Units
Ra-226 Activity Concentration in tailings	7.9	pCi/g
Ra-226 Activity Ratio in slimes vs. sand	4 (default value)	-
Rn-222 Emanation Fraction in slimes	0.35	-
Rn-222 Emanation Fraction in sand	0.15 (default value)	
Fraction Passing #200 Mesh (75 µm)	0.4 (default value)	-
Fraction of pond area with less than 1 m depth	0	
Average pond depth for areas greater than 1 m deep:	2.5	m
Ra-226 Activity Concentration in ponding water	600	pCi/L
Ratio of radium in solution to radium in tailings solids	-	g/cm^3
Effective stagnant water transport coefficient	3E-7	m^2/s

Tailings Zone	Submerged	Saturated	Unsaturated
Surface Area $[m^2]$	1.0E5	-	-
Bulk Density $[g/cm^3]$	2.0	-	-
Porosity	0.41(default value)	-	-
Moisture Contents [dry wt %]	(Saturation)	-	-
Fraction Passing #200 Mesh (75 µm)	0.5 (default value)	-	-
Rn-222 Eff. Diffusion Coefficient $[m^2/s]$	1.2E-9	-	-

Output: Radon flux = 1.27 pCi $m^{-2}s^{-1}$

Input parameters: 1m deep water column

Parameter	Parameter Values Used in On-Line Model	Units
Ra-226 Activity Concentration in tailings	7.9	pCi/g
Ra-226 Activity Ratio in slimes vs. sand	4 (default value)	-
Rn-222 Emanation Fraction in slimes	0.35	-
Rn-222 Emanation Fraction in sand	0.15 (default value)	
Fraction Passing #200 Mesh (75 µm)	0.4 (default value)	-
Fraction of pond area with less than 1 m depth	1	
Average pond depth for areas greater than 1 m deep:	Not applicable	m
Ra-226 Activity Concentration in ponding water	600	pCi/L
Ratio of radium in solution to radium in tailings solids	-	g/cm^3
Effective stagnant water transport coefficient	3E-7	m^2/s

Tailings Zone	Submerged	Saturated	Unsaturated
Surface Area [m^2]	1.0E5	-	-
Bulk Density [g/cm^3]	2.0	-	-
Porosity	0.41(default value)	-	-
Moisture Contents [dry wt %]	(Saturation)	-	-
Fraction Passing #200 Mesh (75 µm)	0.5 (default value)	-	-
Rn-222 Eff. Diffusion Coefficient [m^2/s]	1.2E-9	-	-

Output: Radon flux = 0.91 pCi m^{-2} s^{-1}