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TO: Advisory Board on Radiation and Worker Health Work Group on Linde Ceramics Plant
FROM: Robert Anigstein, SC&A
SUBJECT: Preliminary Review of NIOSH White Paper on Radon in Utility Tunnels at Linde
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Preliminary Review of "Evaluation of Radon Concentrations in the Utility Tunnels at Linde Ceramics"

In a NIOSH White Paper, Allen (2010) developed models to estimate the plausible upper bound of ^{222}Rn concentrations in utility tunnels at Linde Ceramics. The Advisory Board's Work Group on the Linde Ceramics Plant tasked SC&A with reviewing NIOSH's revised approach to the issue of ^{222}Rn in the utility tunnels. We have accordingly reviewed the White Paper and have a number of comments, observations, and findings.

1. Sequential Review

We first present a sequential review of the White Paper, discussing the development and application of the models in the same sequence as presented by Allen (2010). According to Allen, there are two separate sources of radon in the tunnels: ^{226}Ra contamination on the inner surfaces of the tunnels and elevated levels of ^{226}Ra in the soil surrounding the tunnel. In the remainder of this review, "radon" is understood to mean ^{222}Rn and "radium" means ^{226}Ra. For the purpose of the present review, we will treat the methods of calculating the contributions of these two sources as separate models, since each method is specific to the source term considered.

1.1 Part 1 – Radon Present from Radium Contamination Inside the Tunnels

In Part 1, Allen (2010) calculates the contribution of the radium contamination inside the tunnels to the radon concentration, equating the buildup of the daughter product from the decay of the parent to the rate of removal by radioactive decay of the daughter plus the air exchange rate in the tunnel. Site-specific parameters include the surficial concentration of radium, the surface area per linear cm (equal to the perimeter of the cross-section in cm), the volume per linear cm (equal to the area of the cross-section in cm^2), and the air exchange rate. The radium concentration is based on the 95th percentile contamination levels measured by IT (2002); the air exchange rate of 0.1 h^{-1} is taken from the same document. The tunnel in Allen's model has a square cross-section, 2 m high by 2 m wide. The surface area is equal to the lower end of the range of cross-sections presented by IT. This is a claimant-favorable assumption, since the radon concentration due to the surficial contamination by radium is proportional to the $\frac{A}{V}$ ratio, where A is the interior surface area and V is the volume. IT states that the cross-section of the tunnel is cylindrical in some places. The square shape used in the model yields a higher $\frac{A}{V}$ ratio, and is again claimant favorable. We find that the model for estimating the contribution of the radium contamination inside the tunnel to the radon concentration is scientifically correct; the assumed parameters are plausible and claimant favorable.

1.2 Part 2 – Radon Infiltration into the Tunnels

In Part 2, Allen (2010) presents an elegant derivation of the differential equations which he uses to model the infiltration of radon into the tunnel from the surrounding soil. We have verified the derivation up through his Equation 8, which we reproduce in slightly different form:

$$\frac{d^2 c_s}{dx^2} - \frac{\lambda}{D} c_s + \frac{S}{D} = 0 \qquad \textbf{(1)}$$

c_s = radon concentration in pore space in soil

λ = radon decay constant
= $2.0979 \times 10^{-6}\ s^{-1}$

D = diffusion coefficient (cm^2/s)

S = rate of ingrowth of radon from radium in soil (pCi $cm^{-3}\ s^{-1}$)
= $c_p \, \varepsilon \, \lambda \, \rho \left(\frac{1 - n}{n} \right)$

c_p = radium concentration in soil (pCi/g)
ε = radon emanation coefficient
n = porosity of soil

Allen (2010) then presents his Equation 9 as the general solution to his Equation 8:

$$c_s = K_1 e^{rs} + K_2 e^{-rs} + \frac{S}{\lambda} \qquad \textbf{(2)}$$

$$r = \sqrt{\frac{\lambda}{D}}$$

K_1 and K_2 are constants that determine the particular solutions for a given set of boundary conditions.

Allen (2010) then discusses three sets of boundary conditions for each of which he evaluates K_1 and K_2 to derive a solution to Equation (2).[1] We have confirmed the derivation of the particular solution for Allen's symmetrical source boundary conditions, presented by Allen (2010, Attachment A). This solution is mathematically valid for the values of K_1 and K_2 derived by Allen. We will confine the remainder of this review to a discussion of the results for the symmetrical source boundary conditions.

[1] We enclose equation numbers in this review in parentheses to distinguish them from those of Allen (2010).

2. Findings and Observations

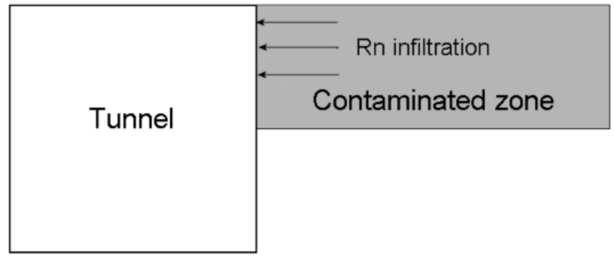

Figure 1. Geometry of Radon Infiltration Model as Described by Allen (2010)

The model geometry described by Allen (2010) is shown in Figure 1. The contaminated zone is assumed to be 100 cm deep. The calculation of the area of the wall subject to infiltration implies that the radium contamination is present on only one side of the tunnel. The tunnel is lined with concrete, which Allen implies is impervious to infiltration by radon. However, he assumes that the concrete has cracks that constitute 10% of the area adjacent to the contaminated zone.

We have several conceptual problems with this model. Allen (2010) likens the cracked concrete to a picket fence, the cracks being the openings in the fence. Let us assign the *x* direction to the lateral movement of radon illustrated in Figure 1, and assume that the cracks, according to the "picket fence" analogy, run in the *z* direction. Since the radon, according to the model, cannot flow through the solid concrete, the *x* component of the concentration gradient at the location of a crack will be different than at the location of the solid concrete. The gradient will therefore also have a *y* component. Furthermore, the stratification of the radium contamination shown in Figure 1 will also create a gradient in the z direction. Thus, the 1-dimensional model is not applicable to this situation.

Another issue is the omission of infiltration through the left side of the tunnel, as illustrated in Figure 1. Also, since the tunnel runs underground, there is likely to be contaminated soil above the tunnel. Furthermore, the radon generated by the decay of naturally-occurring radium in the soil outside the contaminated zone also needs to be accounted for in dose reconstruction under EEOICPA. Radon would thus infiltrate the tunnel through the sides, top, and bottom, again causing a problem for the 1-dimensional model. In addition, the assumption that concrete is impervious to infiltration except in the area of the crack is questionable. According to Yu et al. (1993, table 7.1), the radon diffusion coefficient in concrete has been reported to be as high as 4×10^{-7} m^2/s (4×10^{-3} cm^2/s). Given that 90% of the concrete is not cracked, and given the relatively thin layer of concrete compared to the thick soil layer, the infiltration through concrete needs to be accounted for in what is intended to be a bounding assessment.

We have further questions regarding the values of the parameters used in the model. The value of the soil diffusion coefficient, D = 0.02 cm^2/s, is not claimant favorable. Yu et al. (1993, table 7.1) list values of $(3.2 \pm 1.5) \times 10^{-6}$ m^2/s, which means that D could be as high as 4.7×10^{-6} m^2/s (0.47 cm^2/s)—more than twice the value used by Allen (2010). Since the purpose of Allen's analysis is to produce a bounding assessment, it should use the highest plausible value. The assumption that cracks comprise 10% of the area of the concrete needs to be documented or justified; it appears to be an arbitrary choice.

We also question the assumed radium concentration in the contaminated zone, as well as the depth of the zone. Allen derived the 95th percentile by calculating the median and geometric standard deviation of 711 soil samples. This method is a mix of the rank-order method, by which the middle member of the ranked values (in this case, the 356th value) denotes the median, and an analytical method in which the geometric standard deviation is calculated from the standard deviation of the logarithms of all the values. Such a method is valid where the underlying distribution is known to be lognormal.

We have estimated the 95th percentile radium concentration using a subset of the samples used by Allen (2010). Bechtel (1993, Table 4-6) lists the radium concentrations in 46 soil samples collected in Area 4. According to Davidson (2009, Figure 2-1), Building 30 was located in Area 4. According to an annotated map of the utility tunnels furnished to SC&A during an interview with a Linde site expert, the utility tunnels pass near Building 30, so that some portion of the tunnels is in Area 4 (SC&A 2010, Attachment 1). We calculated the geometric mean and g.s.d. of these data, using all 46 values, and derived a 95th percentile concentration (assuming that the underlying distribution is lognormal) equal to 24.1 pCi/g. The 95th percentile derived using the rank-order method, which makes no assumption about the form of the underlying distribution, is 28 pCi/g. Using Allen's method on this subset of soil samples, we obtain a value of 16.6 pCi/g.

Our analysis demonstrates that Area 4, which lies close to at least a portion of the tunnels, has higher radium levels than the areas covered by the 711 samples analyzed by Allen (2010). Furthermore, the distribution is not lognormal but highly skewed, since the true 95th percentile value obtained by the rank-order method is almost twice the value obtained by taking the median and the g.s.d., while the value obtained by what we shall call a purely analytical method lies in between. We believe that the value used by Allen is not a claimant-favorable representation of the 95th percentile radium concentration in the vicinity of the tunnels.

In another observation, we note that the maximum depth of radioactive contamination in Area 4 is 2.7 m in borehole B29R36 beneath Building 30 (Bechtel 1993). Therefore, the assumption made by Allen (2010) that the contamination is limited to a depth of 100 cm is neither correct nor claimant favorable.

3. Summary and Conclusions

We have confirmed the model presented by Allen (2010) to model the buildup of radon in the tunnel from the decay of radium contamination on the inner surfaces of the tunnel, as well as the parameters used with that model to calculate the radon concentrations generated by that source. We have also confirmed his derivation of the differential equation used to model the 1-dimensional diffusion of radon into the tunnel from the radium-contaminated soil outside the tunnel. We have further confirmed his derivation of a general solution to this equation and of the particular solution of the symmetrical source boundary conditions. We have closely matched the maximum radon concentrations based on this particular solution and the parameters listed in Attachment B to the report.

We do not agree that the 1-dimensional model adequately describes the actual 3-dimensional geometry that governs the diffusion of radon from the soil into the tunnels, nor that the results produced by the model necessarily produce bounding radon concentrations in the tunnels. Using this model, Allen (2010) would need to justify his assumption that cracks constitute 10% of the area of the concrete encasing the tunnel. He also would need to demonstrate that the diffusion of radon through the 90% of the concrete that is intact can be ignored. We do not find that the value of the diffusion coefficient used with the model is bounding or claimant favorable. Similarly, the values assigned to the average radium concentration in the soil and the depth of the contaminated zone used in the analysis are neither bounding nor claimant favorable.

This preliminary review is limited to an analysis of the models and the resulting calculations presented by Allen (2010). It does not address other issues, such as the buildup of radon in the tunnels due to advective transport of radon from the soil, which has been shown to be a significant contributor to indoor radon concentrations.

References

Allen, D. (NIOSH/DCAS). 2010. “Evaluation of Radon Concentrations in the Utility Tunnels at Linde Ceramics.”

Bechtel National, Inc. 1993. “Remedial Investigation Report For The Tonawanda Site Tonawanda, New York,” DOE/OR/21949-300, Vol. 1. Oak Ridge, Tennessee: United States Department of Energy, Oak Ridge Operations Office. [SRDB Ref ID 9026: Section 4.0: “Nature and Extent of Contamination.”]

Davidson, G. R. 2009. “An Exposure Matrix for Linde Ceramics Plant (Including Tonawanda Laboratory),” ORAUT-TKBS-0025, Revision: 01 PC-1. ORAU Team Dose Reconstruction Project for NIOSH.

IT Corporation (IT). 2002. “Dose Assessment for the Existing Contamination Levels within the Linde Site Tunnel Complex: FUSRAP Linde Remedial Action, Tonawanda, New York,” [SRDB Ref ID 49892].

SC&A. 2010. “Linde Worker Interview Notes Niagara Falls, New York, May 19-21, 2010.” SC&A, Inc., Vienna, Virginia, and Saliant, Inc., Jefferson, Maryland.

Yu, C., et al. 1993. “Data Collection Handbook to Support Modeling of Impacts of Radioactive Material in Soil,” ANL/EAIS-8. Argonne, IL: Argonne National Laboratory.