Draft White Paper

EVALUATION OF OCCUPATIONAL ENVIRONMENTAL EXPOSURE TO RADON AT THE FERNALD ENVIRONMENTAL MANAGEMENT PROJECT

Contract Number 200-2009-28555

Prepared by

Robert Anigstein
S. Cohen & Associates
1608 Spring Hill Road, Suite 400
Vienna, Virginia 22182

February 2011

S. Cohen & Associates: ***Technical Support for the Advisory Board on Radiation & Worker Health Review of NIOSH Dose Reconstruction Program***	Document Description: White Paper: Evaluation of Occupational Environmental Exposure to Radon at the Fernald Environmental Management Project Effective Date: Draft –February 2, 2011 Revision No. 0 (Draft)
EVALUATION OF OCCUPATIONAL ENVIRONMENTAL EXPOSURE TO RADON AT THE FERNALD ENVIRONMENTAL MANAGEMENT PROJECT	Page 2 of 27
Task Manager: ____________________ Date: Robert Anigstein, PhD	Supersedes: N/A
Project Manager: __________________ Date: John Mauro, PhD, CHP	Reviewer: John Mauro, PhD

Record of Revisions

Revision Number	Effective Date	Description of Revision
0 (Draft)	2/2/2011	Initial issue

EXECUTIVE SUMMARY

During the meeting of the Advisory Board's Work Group on Fernald on November 9, 2010, SC&A was asked to report on the methods used by NIOSH to reconstruct doses to former employees from occupational environmental exposure to radon[1] at the Fernald Environmental Management Project (FEMP), including information contained in the "Pinney reports."

In the TBD on occupational environmental dose at Fernald, Chu (2006) calculated outdoor radon concentrations and the resulting radon exposures of workers due to the emanation of radon from the radium sources on site. For the period 1952–1988, he utilized a Gaussian plume model of an elevated release to simulate the transport and atmospheric dispersion of radon from the K-65 silos to various on-site receptor points. The simulation assumed that each receptor point was at the center line of the plume whenever the wind was directed toward the given exposure area, and that Pasquill-Gifford class F conditions prevailed all year.

In previous white papers, SC&A has questioned assumptions about the rate of release of radon from the K-65 silos, the major contributors to radon exposures on the site. In our present review, we find the methods used to characterize the transport and atmospheric dispersion of radon to be inappropriate for continuous releases, spanning a period of years, from wide structures such as the silos with release points on or slightly above the domes that form the tops of the silos. Such a model is suitable for emissions from tall stacks with a significant effluent velocity, and for short-term accidental or episodic releases. None of these conditions apply to the releases from the K-65 silos. We also found discrepancies in several results of calculations tabulated in the TBD.

In order to evaluate the impact of the methods used by Chu (2006) to determine atmospheric dilution factors (χ/Q), we performed an independent calculation of the site-wide, annual-average χ/Q that could be used to estimate radon concentrations. Our calculation utilized site-specific meteorological data and site geography, and followed the guidance of the NRC (1977) for evaluating routine atmospheric releases in the vicinity of nuclear power reactors. Our results were less than 50% of the site-wide χ/Q used in the TBD to determine annual radon exposures in units of WLM (working level month). Although not listed in the TBD, the site-wide χ/Q could be inferred from other data presented in the TBD. This χ/Q, although somewhat overstated due to the use of incorrect methodology, does not lead to a claimant-favorable radon assessment, given that the radon emissions from the K-65 silos, especially in the pre-1979 period, may be underestimated by an order of magnitude. Lacking scientific validity, it does not seem to be an appropriate basis for performing dose reconstructions.

We also observed that the estimates of the concentrations of thoron (^{220}Rn) (a decay product of ^{232}Th) in the TBD were based on questionable assumptions and methods. Although thoron is most likely not a major contributor to the radiation exposures of FEMP workers, we believe this radiation source needs to be properly assessed.

[1] In the present report, the term *radon* refers to ^{222}Rn in partial equilibrium with its short-lived progeny.

We conclude that radon concentrations and the resulting radon exposures to workers at the FEMP can be bounded. This conclusion is based on our own success in calculating a site-specific atmospheric dispersion factor appropriate for modeling radon concentrations due to releases from the K-65 silos, and on the assumption that a bounding, scientifically plausible radon release rate would be utilized in the assessment. Comparable methods could be employed to model exposures to thoron.

We also reviewed the two Pinney reports: a 2004 report on the assessment of radon and cigarette smoking of Fernald workers that had been sponsored by NIOSH, and a journal article on the same studies by Hornung et al. (2008).[2] NIOSH had cited these reports as both validating the RAC (Radiological Assessments Corporation) model of radon release, transport, and atmospheric dispersion, and providing data for estimating radon exposures during dose reconstructions. The Pinney study assayed ^{210}Pb, a long-lived daughter product of ^{222}Rn, in window panes of various buildings on the FEMP site by applying CR-39 plastic film to the inner and outer surfaces of windows in various buildings at Fernald for periods of approximately 2 weeks. The film records the activity of ^{210}Po, a short-lived daughter of ^{210}Pb, embedded in the glass. Such assays have been used to measure historical levels of radon in homes. In those cases, the assay was calibrated by use of a test chamber in which glass was exposed to known concentrations of radon under conditions similar to those in the homes being assessed. Since no such data were available for the outdoor exposure of windows to a distant source of radon, the Pinney study utilized the results of the RAC model to calibrate the technique, and then applied the method to other buildings for which RAC model results were unavailable. Therefore, the CR-39 film studies cannot be said to validate the RAC model. An additional attempt to validate the RAC model described in the Pinney reports was to compare the model predictions to on-site measurements made by [redacted] in 1991. We found the comparisons to be inconclusive.

We also checked recent dose reconstructions of lung cancer cases among former FEMP workers to determine if NIOSH was using data from the Pinney reports in current dose reconstructions. We found that this was not the case.

---

[2] Although Dr. Hornung is listed as the senior author, the article states that correspondence should be addressed to Dr. Pinney.

EVALUATION OF OCCUPATIONAL ENVIRONMENTAL EXPOSURE TO RADON AT THE FERNALD ENVIRONMENTAL MANAGEMENT PROJECT

During the meeting of the Advisory Board's Work Group on Fernald on November 9, 2010, SC&A was asked to report on the methods used by NIOSH to reconstruct doses to former employees from occupational environmental exposure to radon[3] at the Fernald Environmental Management Project (FEMP), including information contained in the "Pinney reports." We will first describe the methods used by NIOSH to calculate radon concentrations and the resulting radon exposures of workers at Fernald. We will then present our evaluation of these methods. Finally, we will present summaries of the two Pinney reports and their applicability to dose reconstructions.

1 NIOSH Methodology for Assessing Exposure to Radon

1.1 Estimating Radon Concentrations

In the TBD on occupational environmental dose at Fernald, Chu (2006) calculated outdoor radon concentrations at the site resulting from the emanation of radon from the radium sources on site. The sources addressed in the TBD comprise the two K-65 silos, located near the western boundary of the site, and drummed K-65 materials on the Plant 1 pad, which were said to be present from 1951 to 1953. We will first discuss the contributions of the K-65 silos, which were the only sources in the years 1954–1988 that were addressed in the TBD analyses.

1.1.1 Concentrations Due to Radon Emanation From K-65 Silos 1951–1988

To calculate the radon concentrations resulting from emissions from the K-65 silos at various locations on the site, Chu (2006) calculated a set of atmospheric dilution factors (commonly referred to as *χ/Qs*), assuming an elevated release point and a ground-level receptor location. The equation used to calculate the χ/Q and the parameter values used in the calculation are presented below.

$$\frac{\chi}{Q} = \frac{e^{-\left(\frac{y^2}{2\sigma_y^2}+\frac{h^2}{2\sigma_z^2}\right)}}{\pi\,\sigma_y\,\sigma_z\,u} \qquad (1)$$

χ = outdoor concentration of ^{222}Rn (Ci/m^3)

Q = release rate of ^{222}Rn (Ci/s)

y = crosswind horizontal distance
= 0 m (receptor point on center line of plume)

h = height above ground of release point
= 10 m (based on average stack height at the FEMP site, attributed to Parsons, n/d)

σ_y = crosswind horizontal standard deviation of Gaussian plume (m)

[3] In the present report, the term *radon* refers to ^{222}Rn in partial equilibrium with its short-lived progeny.

σ_z = vertical standard deviation of Gaussian plume (m)

u = wind speed
= 3.2 m/s

The coefficients σ_y and σ_z are functions of distance from the release points and of the Pasquill-Gifford atmospheric stability class. Chu (2006) apparently read the values of these coefficients from the curves shown in Figures 4-3 and 4-4, which present graphs of values of σ_y and σ_z for the six Pasquill-Gifford atmospheric stability classes for distances of 100–10,000 m from the emission source.[4] The figures, which are unattributed, appear to show the same curves as those shown by the Nuclear Regulatory Commission (NRC 1983, Figures 1 and 2). The wind speed of 3.2 m/s is based on the average wind speed for the FEMP site used by Parsons (n/d) in calculating χ/Q values for routine episodic releases.

Table 4-7 of the TBD lists atmospheric dilution factors for a range of distances from the release point spanning 100 to 5,000 m, assuming stability class F. These values are displayed in the fifth column of Table 1. As shown in this table, the maximum elevated χ/Q value calculated by Chu (2006) is for a distance of 500 m. He divided the portions of the FEMP site in which he believed employees might have worked into 11 exposure areas and estimated the distance from each area to the K-65 silos. According to Chu: Distances slightly higher (approaching the 500-m maximum concentration distance) than those scaled from plot plan reproductions were assigned to ensure they were claimant-favorable.

To calculate the radon concentration in a given exposure area, Chu (2006) used the χ/Q calculated for the distance of that area from the K-65 silos and multiplied that value by the frequency that the wind blows from the silos to that location. These frequencies were derived from the wind rose for the FEMP site, based on observations made in 2000, that is presented by Fluor (2001, Figure 1-7) and is reproduced in Figure 4-5 of the TBD. We show this illustration in Figure 1 in color in order to distinguish wind speed from frequency. Chu apparently combined two or more wind sectors to span the angle subtended by each environmental area at the location of the silos. Table 2 lists the frequency-adjusted χ/Q for each exposure area, based on the χ/Q values listed in the fifth column of Table 1.

1.1.2 Concentrations Due to Radon Emanation From K-65 Drums: 1951–1953

The only other radon sources addressed in the TBD were the drummed K-65 materials stored on the Plant 1 pad from October 1951 through June 1953. The radon emanation from these materials was treated as a ground-level release. The χ/Qs at various locations on the FEMP site were calculated by using Equation 1, with the parameter h (height of release point) set to zero. Since the concentrations were calculated along the center line of the plume, the parameter y, the crosswind horizontal distance, was also set to zero. Consequently, the exponential term vanishes and Equation 1 becomes:

$$\frac{\chi}{Q} = \frac{1}{\pi \sigma_y \sigma_z u} \quad \textbf{(2)}$$

[4] The caption for Figure 4-4 mistakenly refers to σ_z as *horizontal* diffusion.

The rest of the methodology was the same as for the elevated releases from the K-65 silos.

Table 1. Values of χ/Q From Ground-Level and Elevated Releases at Various Distances

Distance (m)	χ/Q (s/m^3)					
	Ground-level			Elevated		
	TBD[a]	Calculated[b]	Ratio (Calc. ÷ TBD)	TBD[a]	Calculated[b]	Ratio (Calc. ÷ TBD)
100	2.00e-02	9.58e-03	0.48	5.12e-11	4.80e-07	9,373
150	8.29e-03	4.73e-03	0.57	3.37e-08	3.12e-05	927
200	4.14e-03	2.89e-03	0.70	1.60e-05	1.24e-04	7.78
250	2.48e-03	1.97e-03	0.80	1.09e-04	2.19e-04	2.01
300	1.69e-03	1.45e-03	0.86	2.11e-04	2.79e-04	1.32
350	1.21e-03	1.12e-03	0.92	2.31e-04	3.06e-04	1.32
400	8.85e-04	8.93e-04	1.01	2.71e-04	3.12e-04	1.15
450	7.68e-04	7.33e-04	0.95	2.77e-04	3.05e-04	1.10
500	6.98e-04	6.14e-04	0.88	2.87e-04	2.92e-04	1.02
550	5.92e-04	5.23e-04	0.88	2.71e-04	2.75e-04	1.02
600	4.61e-04	4.53e-04	0.98	2.48e-04	2.58e-04	1.04
650	4.19e-04	3.96e-04	0.95	2.41e-04	2.41e-04	1.00
700	3.51e-04	3.50e-04	1.00	2.23e-04	2.24e-04	1.01
750	2.84e-04	3.12e-04	1.10	2.02e-04	2.09e-04	1.04
1000	1.75e-04	1.92e-04	1.10	1.40e-04	1.49e-04	1.06
2000	6.46e-05	6.45e-05	1.00	5.83e-05	5.83e-05	1.00
5000	1.63e-05	1.80e-05	1.10	1.56e-05	1.72e-05	1.11

[a] Chu (2006, Table 4-7)

[b] Calculated by SC&A (see Section 2.1)

The calculated radon concentrations in each exposure area for 1952–1988 from all sources are listed in Table A-1 of the TBD. These concentrations are increased by the addition of the average background concentrations of 0.47 pCi/L, as measured on site from 1989 to 2000 (attributed to Fluor 2001).

1.1.3 Radon Concentrations: 1989–2002

According to the TBD, the on-site radon concentrations during 1989–1996 were based on measurements with a set of nine high-volume air monitoring stations (AMS). Seven of these AMS were located along the site boundary and two were in the interior of the site. The concentrations in the 11 exposure areas were calculated by using various combinations of these measurements. These measurements, attributed to various unspecified environmental reports, are not listed in the TBD. The calculated ^{222}Rn concentrations in each exposure area for 1989–1996 are listed in Table A-2 of the TBD.

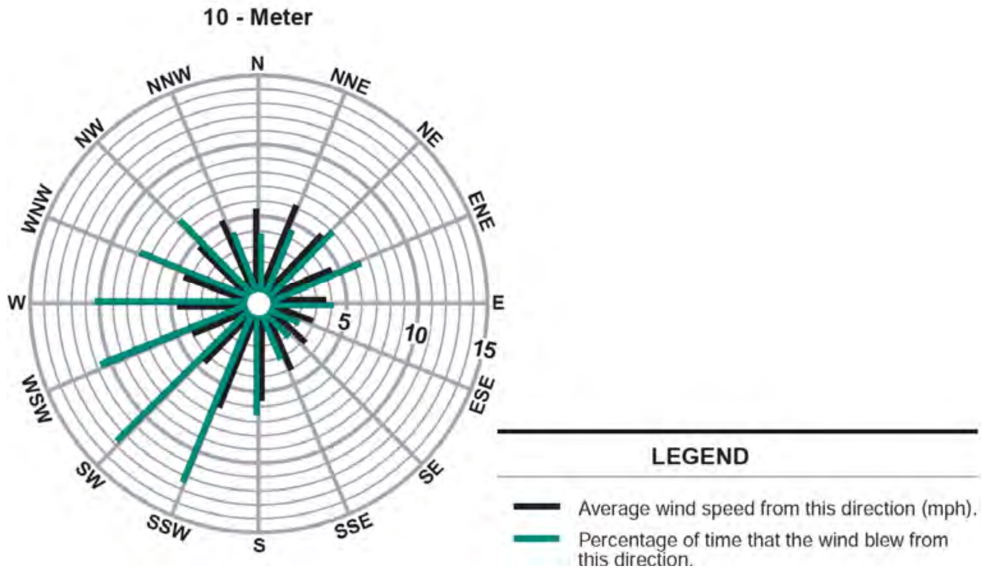

Figure 1. Wind Rose for FEMP Site for 10-m Height for 2000 (Fluor 2001)

Table 2. Frequency-Adjusted χ/Q for Radon Emanations from K-65 Silo in 11 Exposure Areas

EA	Frequency[a] (%)	Distance[b] (m)	χ/Q (s/m^3)	
			TBD[c]	TBD x freq.
1	20	400	2.71e-04	5.42e-05
2	20	1000	1.40e-04	2.80e-05
3	18	1000	1.40e-04	2.52e-05
4	25	450	2.77e-04	6.93e-05
5	30	300	2.11e-04	6.33e-05
6	19	250	1.09e-04	2.07e-05
7	11	500	2.87e-04	3.16e-05
8	15	1000	1.40e-04	2.10e-05
9	18	2000	5.83e-05	1.05e-05
10	23	1000	1.40e-04	3.22e-05
11	8	450	2.77e-04	2.22e-05

[a] Chu (2006, Table 4-9)

[b] Chu (2006, Table 4-8)

[c] Chu (2006, Table 4-7)

For 1997–2002, radon concentrations are equated to the maximum concentrations measured on site and reported in the annual environmental reports (presumably Fluor 1997, 1998, 1999, 2000, 2001, and 2003). For each year, Table A-3 lists a single ^{222}Rn concentration for "Onsite general locations (all EAs)," and a separate value for the K-65 exclusion fence (EA-6).

1.1.4 Concentrations of Thoron (^{220}Rn)

Thoron (^{220}Rn) is a decay product of ^{232}Th (the main constituent of natural thorium). Since thorium was processed and stored at the FEMP at various times during its period of operation, thoron would have been released into the air during these times. An isotope of radon, thoron is an inert noble gas with the same physicochemical properties as ^{222}Rn. One distinguishing characteristic is its short half-life: 55.6 s vs. 3.8 d for ^{222}Rn. As a consequence, given an average wind speed of ~2 m/s (see Section 2.1), the thoron will have almost entirely decayed before traveling more than 10–20 m from its source. However, one of its radioactive daughters, ^{212}Pb, has a half-life of 10.6 h; therefore, ^{212}Pb and its radioactive progeny could remain in the FEMP atmosphere in the form of aerosols. Consequently, thoron and its progeny need to be included in dose reconstructions.

According to the TBD: [F]or 1972 and subsequent years, an activity concentration equal to that of the radon background concentration is assigned to areas close to buildings where thorium was stored. These are identified as Buildings 64, 65, 67, 68, and 69, located in exposure areas 1, 2, and 7. Table A-1 lists a ^{220}Rn concentration of 0.47 pCi/L in each of these three areas (the assumed background level of ^{222}Rn), and zero concentrations to the remaining eight areas. For the years 1989–1996, Table A-2 lists ^{220}Rn concentrations in the range of 0.4–1.0 pCi/L. For the years 1997–2002, Table A-3 lists a single ^{220}Rn concentration for “Onsite general locations (all EAs)” that has one of two values—0.0545 or 0.0818 pCi/L—for each year.

1.2 Assessing Exposures

1.2.1 Exposures to Radon (^{222}Rn)

Radon exposure is often stated in terms of working level months (WLM). One working level (WL) is equal to an exposure to a concentration of 100 pCi/L of the short-lived radon decay products (RDPs) in full equilibrium with its radon parent. However, in most exposure scenarios, the progeny is not in full equilibrium. UNSCEAR (2009) reports that an equilibrium factor of 0.6 might be appropriate for the outdoor environment. The TBD used a conservative value of 0.7, which is said to be an EPA default value. Elsewhere, NCRP Report 78 is cited as the source of this value. Exposures to outdoor ^{222}Rn concentrations are converted to WLM by the following relationship:

$$X_{WLM} = \left(\frac{F_{eq}\, t_y}{C_{WL}\, t_m} \right) C_{Rn-222} \tag{3}$$

X_{WLM} = exposure to ^{222}Rn (WLM)

F_{eq} = equilibrium factor (ratio of ^{222}Rn concentration to RDPs)
= 0.7

t_y = annual exposure duration
= 2,000 h

C_{WL} = concentration of RDPs equal to 1 WL
= 100 pCi/L

t_m = nominal monthly exposure duration in workplace
= 170 h

$C_{Rn\text{-}222}$ = ^{222}Rn concentration (pCi/L)

The factor in parentheses in Equation 3 is equal to approximately 0.08235. Thus, to calculate the annual exposure of a full-time employee, one would multiply the average ^{222}Rn concentration (in pCi/L) by 0.08235 to obtain the exposure in units of WLM.

Tables A-1 and A-2 of the TBD list the annual radon exposure (in WLM) corresponding to each ^{222}Rn concentration in each exposure area for the years 1952–1988 and 1989–1996, respectively. Chu (2006) reported calculating a lognormal distribution of the annual exposures in the 11 exposure areas for each of these 45 years. According to Chu: The site-wide intakes for radon (^{222}Rn) are represented by the 95th-percentile values from a lognormal distribution and are listed in Table 4-12, which includes the Geometric Mean (GM) and Geometric Standard Deviation (GSD) of the lognormal distribution.

Table A-3 of the TBD lists the annual radon exposure (in WLM) corresponding to each ^{222}Rn concentration in that table for the years 1997–2002 (see Section 1.1.3). Table 4-12 lists the average of the two exposures for each year that are listed in Table A-3. (An exception is the value for 2002, which appears to be erroneous.)

1.2.2 Exposures to Thoron (^{220}Rn)

Chu (2006) also uses Equation 3 to assess exposures to thoron (^{220}Rn), with the following changes in parameter values:

F_{eq} = equilibrium factor (ratio of ^{220}Rn concentration to RDPs)
= 0.1

C_{WL} = concentration of RDPs equal to 1 WL
= 7.47 pCi/L

Tables A-1 and A-2 of the TBD list the annual thoron exposure (in WLM) in each of the three exposure areas for which ^{220}Rn concentrations are listed for the years 1952–1988 and 1989–1996, respectively. Since the FEMP facilities were divided into 11 exposure areas, the sum of the three thoron exposures for each year was divided by 11 to yield the site-wide thoron exposure (labeled as *intake*) listed in Table 4-12. The exposures corresponding to the ^{220}Rn concentrations in Table A-3 for the years 1997–2002 are listed there and in Table 4-12.

2 Evaluation of NIOSH Methodology for Calculating Radon and Thoron Concentrations

2.1 Evaluation of Concentrations Due to Radon Emanation From K-65 Silos

We first attempted to verify the χ/Q values listed in Table 4-7 of the TBD and reproduced in Table 1. Rather than attempting to read the graphs in Figures 4-3 and 4-4 of the TBD, we utilized algorithms derived by Eimutis and Konicek, who fitted sets of power functions to the original Pasquill-Gifford curves. These functions are incorporated into the computer code

XOQDOQ, described and listed by Sagendorf et al. (1982, Subroutine POLYN). A more detailed discussion is presented in Appendix A of the present report.

As shown in Table 1, our values for elevated releases, calculated using Equation 1 and the same parameters listed by Chu (2006), were up to 4 orders of magnitude higher than those calculated by Chu. For the distances used to assign χ/Qs to the 11 exposure areas, which range from 250 to 2,000 m, our calculated values ranged from twice the TBD value to approximately equal. Although Chu used a different method of approximating the values of σ_y and σ_z, the magnitude of some of the discrepancies is surprising.

We confirmed that Parsons (n/d) used an average wind speed of 3.2 m/s and stability class F for calculating χ/Qs at the site boundary for episodic, short-term releases. However, no calculations or observations were presented in that report to justify that value. It is most likely based on the cited average wind speed of 7.1 mph for the Cincinnati area, which corresponds to 3.2 m/s. Killough et al. (1993, Table ES-13) listed the annual joint frequencies of wind speed, direction, and stability class recorded at the FEMP during the 5-year period, 1987–1991, which are shown in Table B-1 of Appendix B of the present report. Using these data, we calculated an average wind speed of 2.12 m/s. We repeated that analysis by tabulating the values estimated from the wind rose for the year 2000 shown in Figure 1 (a less accurate determination) and derived a value of 2.18 m/s, which is consistent with our first analysis. We thus question the value of 3.2 m/s cited by Parsons and adopted in the TBD. We could not confirm the reference to an average stack height of 10 m, attributed to Parsons (n/d).

2.1.1 Alternative Calculation of Annual-Average, Site-Specific χ/Q

The above discrepancies aside, we find that the method of calculating χ/Q is inappropriate for the estimation of average annual radon exposures of workers at Fernald. The methodology presented in the TBD appears to be based on that used by Parsons (n/d). Parsons, as stated earlier, assessed the off-site impacts of episodic short-term releases and appropriately assumed a set of bounding atmospheric conditions for a single release. Since one cannot predict the wind direction at the time of the accident, such an assessment normally assumes that the wind is blowing steadily in the exact direction of the receptor under the highest plausible stability class. The receptor thus experiences the maximum concentration of the released airborne material. Such conditions are represented by Equations 1 and 2 in the present report, with the crosswind distance, *y*, set to zero. According to NRC (1983), such steady conditions could prevail for a period of 2 hours following an accident.

For an assessment of steady releases, such as the seepage of radon from the K-65 silos, a more appropriate methodology is one that is presented by NRC (1977) for evaluating routine atmospheric releases in the vicinity of nuclear power reactors. Instead of assuming that the plume is always directed at the receptor location, this methodology uses site-specific meteorological data to calculate sector-averaged χ/Qs. The sector-averaged Gaussian plume model assumes that within each sector the pollutant concentration will not vary with the angular coordinate (i.e., the direction) of the receptor with respect to the emission source. Site-specific data are used to construct joint-frequency tables which typically categorize hourly observations of wind speed and direction into 6 (sometimes 7) stability classes, 16 compass directions, and 6 wind-speed ranges. Such tables can be used to calculate the annual-average χ/Q at any distance in a given sector comprising one of the 16 compass directions.

Another objection to the use of Equation 1 is the assumption of an elevated release. According to NRC (1977), an elevated release point can be used only if the stack is at least twice the height of adjacent structures. As shown in Figure 2, that is clearly not the case for the K-65 silos. Such an assumption results in an extremely low χ/Q near the silos.

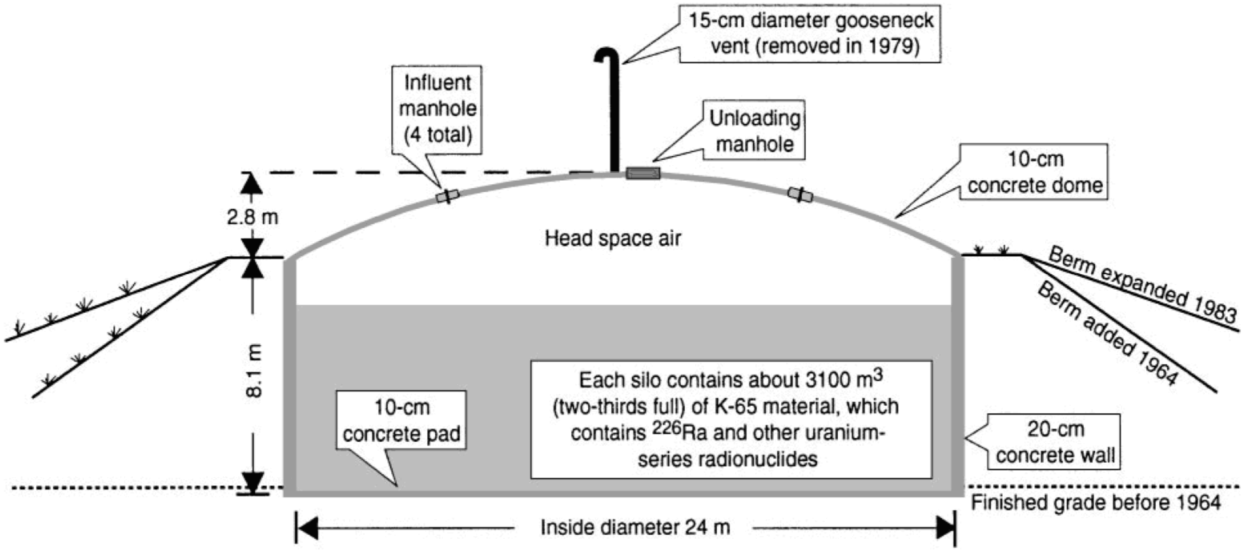

Figure 2. Cross-Sectional View of One of the K-65 Silos (Killough and Schmidt, 2000)

In order to evaluate the overall effect of the χ/Q calculation on the assessment of radon exposure, we performed an independent calculation of a site-wide χ/Q for ground-level releases from the K-65 silos. In this calculation, intended to serve as an example of how the guidance presented by NRC (1977) could be applied to the FEMP site, we assumed workers could have been present in any accessible area of the site, which includes almost the entire site but excludes the area inside the security fence enclosing the K-65 silos. We divided this accessible area into approximately 10,000 contiguous squares, each measuring 20 x 20 m. We then calculated the annual-average χ/Q for each square, using the distance and direction of the center of each square from the center of the two K-65 silos, the joint frequency data presented in Table B-1, and the following equation, which is based on NRC (1977) guidance for ground level releases:

$$\frac{\chi}{Q} = \frac{2.032}{x} \sum_{ij} \frac{f_{ijk}}{u_i \Sigma_{zj}(x)}$$

$$\Sigma_{zj}(x) = \left(\sigma_{zj}^2(x) + \frac{D_z^2}{2\pi} \right)^{1/2} \qquad \textbf{(4)}$$

$$\leq \sqrt{3}\ \sigma_{zj}(x)$$

f_{ijk} = joint frequency of Pasquill stability class j and wind speed i in sector k

$\sigma_{zj}(x)$ = vertical standard deviation of plume for stability class j at distance x (m)

x = distance to receptor (m)

u_i = mean speed of wind-speed range i in sector k (m/s)

$\Sigma_{zj}(x)$ = vertical standard deviation of plume at distance x, with correction for additional dispersion within building wake cavity (m)

D_z = maximum adjacent building height either up- or downwind from release point

The factor 2.032 is calculated as follows:

$$\frac{\sqrt{\frac{2}{\pi}}}{\theta_w} = 2.032$$

θ_w = angular width of wind-direction sector (radians)

$= \frac{2\,\pi}{16}$

Using this methodology, we calculated the annual-average χ/Q for the FEMP site to be 1.29×10^{-5} s/m^3 and the 95th percentile of the values for the 9,586 individual squares to be 4.07×10^{-5} s/m^3. A more detailed description of this analysis is presented in Appendix B.

The TBD does not explicitly list a site-wide χ/Q for releases from the K-65 silos. We attempted to back-calculate this value from the annual radon exposures listed in Table 4-12. We first had to determine the assumed release rate from the K-65 silos for any year between 1954 and 1988, when the exposures were based entirely on the radon emanations from the silos. We did this by dividing the radon concentration at one of the exposure areas, listed in Table C-1, by the frequency-adjusted χ/Q listed in Table 2 of the present report.[5] Using 1960 data as an example, we calculated a release rate of 9,000 Ci/y, or 2.85×10^{-4} Ci/s. (Voilleque et al. 1995, Table J-35, lists a 95th percentile rate of 8,700 Ci/y for mid-September 1958-June 1979.) The geometric mean ^{222}Rn exposure rate, listed in Table 4-12, is 0.686 WLM for 1960. Dividing this value by the WLM conversion factor of 0.08235 listed in Section 1.2.1 of the present report, we obtained a ^{222}Rn concentration of 8.33 pCi/L or 8.33×10^{-9} Ci/m^3. To determine the concentration due to the emanation from the K-65 silos, we subtracted the site background concentration of 0.47 pCi/L to obtain a value of 7.86 pCi/L or 7.86×10^{-9} Ci/m^3. Dividing by the release rate in Ci/s yielded a $\chi/Q = 2.76 \times 10^{-5}$ s/m^3. The corresponding 95th percentile value, calculated in the same manner, using the 95th percentile exposure of 1.60 WLM listed in Table 4-12, is 5.98×10^{-5} s/m^3. The arithmetic mean of the χ/Q lognormal distribution, calculated from the geometric mean and the GSD of the 1960 WLM values presented in Table 4-12, is equal to 2.98×10^{-5} s/m^3.

---

[5] This step is necessitated by the difficulty of determining an exact value from Figure 4-1 of the TBD, which depicts the releases from the K-65 silos.

We thus observe that the annual-average χ/Qs, calculated using site-specific data and a methodology appropriate to continuous, steady releases from the K-65 silos, are approximately one-half the values inferred from the TBD data. Although the TBD results would thus appear to be claimant-favorable, they are based on a faulty model whose use for dose reconstructions is questionable.

2.1.2 Further Observations on the Calculation of Radon Concentrations

Under EEOICPA, natural background radiation does not enter into a compensation decision and should therefore not be included in dose reconstructions. Although a small effect in the present case, the addition of background radon concentrations to the contribution from on-site radon sources is incorrect. Furthermore, we could not confirm the background concentration of 0.47 pCi/L. Chu (2006) attributes it to Fluor (2001); however, according to that report: The range of average background radon concentrations was 0.2 to 0.3 pCi/L (Fluor 2001, p. 93). This has no impact on dose reconstructions but reflects on the scientific accuracy of the TBD.

We found the description of the method used to derive site-wide χ/Qs from a distribution of the χ/Qs at the 11 exposure areas to be unclear—we were unable to reproduce the values in Table 4-12 by applying the procedure described in the TBD. As we understand it, the results in Table 4-12 for the years spanning 1954–1988 were based on the same release point and the same χ/Q values, and differed only because the radon release rates from the K-65 silos were assumed to change during this period. If that were the case, the GSD, which depends only on the distribution of χ/Qs at the 11 exposure areas, should be the same for the entire period. Instead, the GSD changes for each assumed release regimen, i.e., it is different for each of the different release rates for the periods 1954–1958, 1959–1979, 1980–1987, and 1988.

The use of Equation 2 for ground-level releases from the drummed K-65 materials, together with the same assumptions about the wind speed and stability class used to assess assumed elevated releases, poses the same issues as we discussed in connection with Equation 1, except that the assumption of a ground-level release is appropriate in this case.

Although the focus of the present review is the estimation of radon concentrations at Fernald, we note in passing a fallacy in calculating the release rates of radioactive particulates based on monitoring data during the later years of operation. According to the TBD: The radionuclide release rates used to estimate EA concentrations were the average of those release rates calculated for AMS 8 and 9, using ground release (χ/Q)s. Since the χ/Qs for ground level releases were overstated, the calculated release rates, which involve dividing a measured concentration by the χ/Q, would be understated. A more appropriate technique would be to use annual-average χ/Qs, based on site-specific meteorological data, for the specific source and receptor locations.

2.2 Evaluation of Thoron Concentrations

The calculation of thoron concentrations in the TBD was based on the assumptions that thoron was found only in the vicinity of the five buildings used as a thorium (^{232}Th) repository in 1972 and subsequent years and that the concentration of the gas is equal to *background* concentrations of radon.

The second assumption is valid for thoron that is part of the natural background. Since radon and thoron are decay products of ^{226}Ra and ^{232}Th, and since activity concentrations in soil of these two parent nuclides in soil have a world-average ratio of about 1.2:1, it is not surprising that radon and thoron are found in the same ratio near the surface of the ground (NCRP 1976). It would thus be appropriate to estimate the *background* concentrations of thoron on the basis of the background concentrations of radon. However, the background radon concentrations bear no relationship to thoron concentrations resulting from the processing or storage of thorium at the FEMP. Furthermore, since thorium was present on site at various times prior to 1972, setting the thoron concentrations to zero during these earlier years is not scientifically correct nor claimant favorable.

3 Findings and Conclusions

Although we do not accept the methodology of calculating outdoor concentrations of ^{222}Rn presented in the TBD, we believe that such concentrations can be bounded by using site-specific meteorological data, such as that shown in Table B-1 of Appendix B; an appropriate atmospheric dispersion model, such as the one described in Section 2.1.1; and a bounding source term.

Although thoron is typically not a large contributor to radiation exposures, we believe that, given the presence of large quantities of thorium on the FEMP site, thoron emissions should be modeled. A bounding calculation would assume an appropriate release fraction from the thorium and atmospheric transport with decay of the thoron and deposition of the particulate RDPs, using models described by the NRC (1977) or a comparable methodology. As is the case with radon, we believe that thoron concentrations can be bounded by applying appropriate data and methods.

SC&A has previously found that the disequilibrium between the ^{226}Ra activities and the activities of ^{210}Pb in the K-65 silos, reported by Voilleque et al. (1995), if due to the escape of radon from the silos, implied a source term that is an order of magnitude greater than what was modeled by Voilleque et al. and used as the basis of on-site radon concentrations in the TBD. On further examining the distribution of radionuclides in the two silos listed by Voilleque et al. (1995, Table J-5), we note that not only are the ^{210}Pb activities about 50% less than the expected values if there were no escape of radon, the ^{210}Pb:^{226}Ra displays a trend in the three horizontal layers of the K-65 wastes: the ratio tends to be lower in the upper layer and greater in the bottom layer. This would be expected, since more radon would escape from the wastes nearest the surface. We believe that NIOSH should revisit the principal radon source—the K-65 silos—and either revise the magnitude of the emissions or present an analysis that explains the large differences between the expected and observed ^{210}Pb activity concentrations.

Additional sources of radon include the drums of K-65 material which were present from 1951 to 1953, and are addressed in the TBD. However, the Q-11 silos that are described by Hornung et al. (2008) (see Section 4.1) also need to be considered in the calculation of on-site radon concentrations during 1952–58. The exposures to radon from these sources can also be bounded by the application of site-specific data and appropriate methodology.

4 Review of the Pinney Reports

SC&A was also asked to explain how the information in the Pinney reports was being used, or could be used, in assigning radon exposures at Fernald. There are two separate reports: a 2004 report on the assessment of radon and cigarette smoking of Fernald workers, that had been sponsored by NIOSH, and a journal article on these studies by Hornung et al. (2008). We will begin by reviewing the journal article.

4.1 Hornung et al. (2008)

The following is a targeted summary of "Estimation of Radon Exposures to Workers at the Fernald Feed Materials Production Center 1952–1988" (Hornung et al. 2008), as it pertains to dose reconstruction at Fernald.[6]

In order to perform a historical dose reconstruction aimed at correlating risk of lung cancer to radon exposure, the authors applied CR-39 film to the inner and outer surfaces of windows in various buildings at Fernald for periods of approximately 2 weeks. The film records the activity of ^{210}Po embedded in the glass. Being the short-lived daughter of ^{210}Pb, ^{210}Po ($t_{½}$ = 138 d) can be used to calculate the cumulative activity of ^{210}Pb, which in turn can be used to estimate the deposition of ^{222}Rn progeny (primarily ^{214}Bi and ^{214}Po) on the glass. When ^{214}Po decays by α emission, the recoil momentum of the resulting atom of ^{210}Pb, corresponding to an energy of 147 keV, may embed the atom in the glass. Thus, the ^{210}Po tracks recorded in the film are a measure of the time-integrated concentration of the short-lived ^{222}Rn progeny at the surface of the glass. Both the temporal variation of the concentration and the deposition rate of the particles (which is also a function of the attached/unattached fractions), as well as the radioactive decay of ^{210}Pb and the equilibrium concentration of ^{210}Po, must be accounted for.

To obtain the deposition rate, the authors assumed that the historical ^{222}Rn concentrations at locations on site are calculated by the RAC (Radiological Assessments Corporation) model, described by Voilleque et al. (1995). During the course of the investigation, they discovered another source of ^{222}Rn on site: the Q-11 silos that were located near the production area. Being unsealed, these silos were the dominant source of ^{222}Rn in the production area during 1952–1958. The authors therefore used the films from windows 1,000 m away from the Q-11 silos—they deemed that these were exposed only to ^{222}Rn from the K-65 silos and from natural background. They make the puzzling statement: ^{210}Po measurements in distant buildings were similar to background measurements (natural background plus K-65 emissions), which provided some assurance that they were relatively unaffected by the Q-11 source. This appears to be a circular argument, but perhaps they have not clearly stated their reasoning.

In any case, the films from these *distant* buildings, together with the integrated ^{222}Rn concentrations from the RAC model, were used to calculate the deposition rate of ^{210}Pb. This deposition rate was then used to calibrate the CR-39 films. The films from buildings near the Q-11 silos were used to assess the ^{222}Rn exposures from that source by calculating a

[6] Although Dr. Hornung is listed as the senior author, the article states that correspondence should be addressed to Dr. Pinney.

2-dimensional mathematical surface which served to smooth the variation between the film readings at individual locations and to interpolate the exposures at locations where no film measurements were taken.

Hornung et al. (2008) also discuss measurements of ^{222}Rn concentrations, made in 1991 by [redacted] for his Master's thesis, in the vicinity of five buildings on the Fernald site. ([redacted] also measured concentrations in the vicinity of the K-65 silos, but those results are not cited by these authors.) The hourly means at each location were used to calculate a geometric mean and a GSD at each location during each of the three work shifts, resulting in 15 data sets. These results were compared to the results of the RAC model for 1988, using on-site joint frequency data for 1986–1991. The model predicts different ^{222}Rn release rates during each shift. The authors thus conclude that the [redacted] data validate the RAC model.

We digitized the graphical representation of the data presented by Hornung et al. (2008, Figure 1) and calculated the ratio of the model prediction to the geometric mean of the [redacted] data. The ratios ranged from 0.31 to 2.95, with a mean of 1.27 and a standard deviation of 0.77. For 12 of the 15 data sets, the model predictions lie well within the 5th to 95th percentile range of the measured values. In the remaining three cases, the model predictions are at or below the 5th percentile of the measured values. One problem with this comparison is that [redacted] s measurements were made over a period of 7 months—May to September—while the model utilized joint frequency data for the entire 5-year period. Since meteorological conditions vary during the seasons, the two data sets are not strictly comparable. Thus, the data cannot be said to validate the model, although they indicate that the predictions are plausible for the year 1988. What is more important, the comparison sheds no light on the radon release rates during earlier years, particularly for the years prior to 1979, when the silos were capped.

Hornung et al. (2008, Appendix A) present a discussion of a simplified version of the RAC model used to calculate radon transport from the K-65 silos to downwind locations. In brief, the model utilizes widely-scattered empirical data which are folded into a mathematical model of an area source (i.e., the top of the dome of the silo, modeled as a flat circle), assuming ground-level releases and calculating ground-level concentrations. The measurements include one set, presumably on site, spanning the period July 2, 1985–July 2, 1986, at distances of 30–600 m (the reference point [origin] for the distance is not given) plus a second set, off site, at distances of ~320–1900 m, during 1981–1987. The data are highly dispersed: for example, values of χ/Q between 250 and 320 m vary by a factor of 30.

4.2 Pinney et al. (2004)

We next reviewed the “Condensed Final Report for Radon and Cigarette Smoking Exposure Assessment of Fernald Workers” (Pinney et al. 2004). This earlier report provides more details about the history of the K-65 silos, as well as an account of the comparison of the [redacted] data with the predictions of the RAC model. Presented in tabular form, the comparison includes only four of the five locations cited by Hornung et al. (2008). The values given by Pinney et al. (2004, Table 2) are markedly different from the data presented by Hornung et al. (2008, Figure 1). The ratios of the model values in the two reports are fairly consistent for a given shift at the four locations common to both reports, but vary markedly among the three shifts. The ratios of the measurements presented by Pinney et al. (2004, Table 2) to the geometric mean values depicted by Hornung et al. (2008, Figure 1) show no such pattern. This earlier report also erroneously states that the window glass measurements of ^{210}Po validate the RAC model, whereas the results of the RAC model were actually used to calibrate the ^{210}Po measurements to estimate the time-integrated ^{222}Rn concentrations.

4.3 Application of the "Pinney Reports" to Dose Reconstructions of Fernald Employees

4.3.1 Review of Recent Case Files

We first attempted to determine if, as suggested by NIOSH, information in the Pinney reports were being used in the dose reconstructions. We selected cases with ICD codes 162.1–162.9, which include primary cancers of the respiratory tract, the tissues most commonly affected by the inhalation of radon RDPs. We looked only at dose reconstructions completed in 2010, which would reflect the most current NIOSH procedures.

We found 12 completed cases that met these criteria. Of these, ten DRs were deliberate underestimates: environmental exposures were omitted, since the cases were compensable without assessing the contributions of these pathways. Thus, no radon exposures were calculated. In the two remaining cases, radon exposures, expressed as WLM for each year of employment, were copied from Chu (2006, Table 4-12). No other information was utilized in these assessments. We also examined the files of five recent cases for which no DRs were completed. No information regarding radon exposures that could be used in dose reconstructions was found. We thus found no indication that any data, other than from the TBD, were being used in dose reconstruction.

4.3.2 Applicability of "Pinney Reports" to Dose Reconstructions

The analysis of ^{210}Pb in window panes at the FEMP site was used by Dr. Pinney and her colleagues in performing a building-by-building radon exposure assessment. Such an assessment was based on the assumption that the radon exposure history was known for several buildings, based on data and computation performed by RAC personnel. It was then possible to calibrate the ^{210}Po tracks in the CR-39 films exposed to the window panes in these buildings against the radon exposures of these glass panes. This calibration factor could then be used to assess the radon exposures of other buildings, whose radon exposure history was unknown. However, if the assumed radon exposures for the calibration films were incorrect, then the calibration factors would also be incorrect, and the assessment of the radon exposures of other buildings would be invalid.

References

Chu, S. L. T. 2006. "Fernald Environmental Management Project – Occupational Environmental Dose," ORAUT-TKBS-0017-4, Rev. 1. ORAU Team Dose Reconstruction Project for NIOSH. http://www.cdc.gov/niosh/ocas/pdfs/tbd/frnld41.pdf

Fluor Fernald, Inc. (Fluor). 1997. "1996 Integrated Site Environmental Report."

Fluor Fernald, Inc. (Fluor). 1998. "1997 Integrated Site Environmental Report," 51350-RP-0001

Fluor Fernald, Inc. (Fluor). 1999. "1998 Integrated Site Environmental Report," 51350-RP-0005

Fluor Fernald, Inc. (Fluor). 2000. "1999 Integrated Site Environmental Report," 51350-RP-0010

Fluor Fernald, Inc. (Fluor). 2001. "2000 Integrated Site Environmental Report," 51350-RP-0015

Fluor Fernald, Inc. (Fluor). 2003. "2002 Integrated Site Environmental Report."

Hornung et al. 2008. "Estimation of Radon Exposures to Workers at the Fernald Feed Materials Production Center 1952–1988." *Journal of Exposure Science and Environmental Epidemiology 18*, 512-523.

Killough, G. G., and D. W. Schmidt. 2000. "Uncertainty Analysis of Exposure to Radon Released from the Former Feed Materials Production Center." *Journal of Environmental Radioactivity*, *49*, 127–156.

Killough, G. G., et al. 1993. "The Fernald Dosimetry Reconstruction Project, Task 4: Environmental Pathways—Models and Validation," RAC Report No. CDC-3. Neeses, South Carolina: Radiological Assessments Corporation.

National Council on Radiation Protection and Measurements (NCRP) 1976. "Environmental Radiation Measurements," NCRP Report No. 50. Bethesda, Maryland: Author.

Nuclear Regulatory Commission (U.S.) (NRC). 1977. "Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors, Revision 1," Regulatory Guide 1.111. Washington D.C.: Author.

Nuclear Regulatory Commission (U.S.) (NRC). 1983. "Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants, Revision 1," Regulatory Guide 1.145. Washington D.C.: Author.

Parsons. n/d. "Safety Analysis Report for the Warehoused Thorium Overpacking Building." Cincinnati, Ohio: Fernald Environmental Restoration Management Corporation.

Pinney et al. 2004. “Condensed Final Report for Radon and Cigarette Smoking Exposure Assessment of Fernald Workers.” University of Cincinnati (submitted to the National Institute of Occupational Safety and Health). [SRDB Ref. ID: 26771].

Sagendorf, J. F., J. T. Goll, and W. F. Sandusky. 1982. “XOQDOQ: Computer Program for the Meteorological Evaluation of Effluent Releases at Nuclear Power Stations,” NUREG/CR-2919. Washington, D.C.: U.S. Nuclear Regulatory Commission.

Tomes, T. 1997. “Technical Basis for Internal Dosimetry at the FEMP,” SD-2008, Rev. 1. Fluor Fernald, Inc.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 2009. “Effects of Ionizing Radiation: UNSCEAR 2006 Report, Volume II - Report to the General Assembly, with Scientific Annexes C, D, and E. Annex E - Sources-to-effects assessment for radon in homes and workplaces.” United Nations, United Nations Office at Vienna. http://www.unscear.org/docs/reports/2006/09-81160_Report_Annex_E_2006_Web.pdf

Voilleque, P. G., et al. 1995. “The Fernald Dosimetry Reconstruction Project—Tasks 2 and 3: Radionuclide Source Terms and Uncertainties,” RAC Report CDC·5. Neeses, South Carolina: Radiological Assessments Corporation.

Appendix A

CALCULATION OF PASQUILL-GIFFORD ATMOSPHERIC DISPERSION COEFFICIENTS

The standard deviations in the vertical and horizontal directions for the Gaussian plume atmospheric dispersion model (known as the Pasquill-Gifford dispersion coefficients) are calculated by evaluating the following power functions:

$$\sigma_{y_i}(x) = a_i x^{b}$$
$$\sigma_{z_i}(x) = c_{ij} x^{f_{ij}} + g_{ij} \qquad (i = 1, 2, \ldots, 6; j = 1, 2, 3)$$

$\sigma_{yi}(x)$ = crosswind horizontal standard deviation of Gaussian plume for Pasquill-Gifford stability class *i* at distance *x* (m)

$\sigma_{zi}(x)$ = vertical standard deviation of Gaussian plume for Pasquill-Gifford stability class *i* at distance *x* (m)

a_i = constant for stability class i (1 = A, 2 = B, etc.)

x = distance of source to receptor

b = 0.9031

c_{ij}, f_{ij}, g_{ij} = constants for stability class *i* and distance range *j*

j = 1 (x < 100 m)
= 2 (100 m < x < 1,000 m)
= 3 (x > 1,000 m)

In all cases, $\sigma_z \leq 1{,}000$ m, regardless of the calculated value.

The values of the constants, which are listed in Table A-1, are from the program XOQDOQ (Sagendorf et al. 1982, p. A.42). They were derived by Eimutis and Konicek (as cited by Sagendorf et al.) from curves originally plotted by Gifford.

Table A-1. Constants Used to Determine Horizontal and Vertical Dispersion Coefficients

Constant	Distance range	Stability Class					
		A	B	C	D	E	F
a	all	.3658	.2751	.2089	.1471	.1046	.0722
c	1	.19200	.1560	.1160	.0790	.0630	.0530
	2	.00066	.0382	.1130	.2220	.2110	.0860
	3	.00024	.0550	.1130	1.260	6.730	18.05
f	1	.9360	.9220	.9050	.8810	.8710	.8140
	2	1.941	1.149	.9110	.7250	.6780	.7400
	3	2.094	1.098	.9110	.5160	.3050	.1800
g	1	.0000	.0000	.0000	.0000	.0000	.0000
	2	9.270	3.300	.0000	-1.700	-1.300	-.3500
	3	-9.600	2.000	.0000	-13.00	-34.00	-48.60

Reference for Appendix A

Sagendorf, J. F., J. T. Goll, and W. F. Sandusky. 1982. “XOQDOQ: Computer Program for the Meteorological Evaluation of Effluent Releases at Nuclear Power Stations,” NUREG/CR-2919. Washington, D.C.: U.S. Nuclear Regulatory Commission.

Appendix B

ALTERNATIVE CALCULATION OF χ/Q: SUPPLEMENTAL INFORMATION

As discussed in Section 2.1.1, SC&A performed an alternative calculation of the annual-average χ/Q for the FEMP site. A more detailed discussion of the methods and input data is presented in this appendix.

B.1 Site-Specific Meteorological Data

Meteorological data were recorded at the FEMP by an on-site tower, beginning in August 1986. These data comprised hourly readings of wind speed and direction, and the vertical temperature gradient (ΔT/Δz). The last parameter is used to determine the Pasquill-Gifford stability class. Killough et al. (1993, Appendix E) obtained these hourly data. They processed the data for the five whole years—1987–1991—to produce a table of the annual joint frequencies of wind speed, direction, and stability class occurring at the FEMP during this 5-year period. This table (Killough et al. 1993, Table ES-13) is presented here as Table B-1. Although some observations at the FEMP would fall into the highest stability class, class G, the software used by Killough et al. categorized all the data into six stability classes, so that occurrences of class G were combined with those of class F. This leads to an underestimate of χ/Q for the periods when class G conditions prevailed.

The frequencies in Table B-1 are normalized separately for each stability class (i.e., the sum of the frequencies for each class equals 1). It is therefore necessary to multiply each frequency by the total frequency of occurrence of each class to obtain the joint frequency of occurrence of wind speed, direction, and stability class for any particular combination of these parameters. In utilizing these data in calculating annual-average χ/Qs for the FEMP site, we set each wind speed to the middle of the range shown in Table B-1. The wind speed of the highest range (> 10 m/s) was assigned the claimant-favorable value of 11 m/s.

Another shortcoming of using these data to calculate radon concentrations on the FEMP site for time periods from 1952 on is that the meteorological conditions for 1987–1991 may not correctly represent those during the earlier time periods. Killough et al. (1993, Appendix E) compared the on-site data with data sets from nearby locations, notably the Cincinnati Airport at Covington, Kentucky, whose data sets span the period 1948–1991. They found that the Cincinnati Airport data consistently underestimates χ/Qs, as compared to the on-site data.

We arrived at the same conclusion when we initially utilized Cincinnati Airport data to perform the site-wide χ/Q calculations described in the present report. We had used two data sets, spanning the periods 1958–1962 and 1970–1974. These data were part of the CAP88-PC computer code package (EPA 1993) and offered the advantage of being compatible with computer software that we had created for an earlier project. When we ultimately decided to use the FEMP data instead, we found that the Cincinnati Airport data had resulted in site-wide annual-average χ/Q that were less than 50% of the values obtained with the on-site data.

Table B-1. Annual Joint Frequencies for FEMP: 1987–1991

	Wind speed range (m/s)						Total	Wind speed range (m/s)						Total
	0–2	2–4	4–6	6–8	8–10	>10		0–2	2–4	4–6	6–8	8–10	>10	
	Class A frequency 0.06374							Class B frequency 0.03104						
N	0.00548	0.01482	0.01201	0.00000	0.00000	0.00000	0.03231	0.00805	0.03271	0.00926	0.00152	0.00000	0.00000	0.05154
NNE	0.01088	0.01509	0.01007	0.00122	0.00039	0.00000	0.03765	0.00641	0.01174	0.01408	0.00155	0.00000	0.00000	0.03378
NE	0.01762	0.03981	0.00770	0.00040	0.00000	0.00000	0.06553	0.01023	0.03650	0.01330	0.00000	0.00000	0.00000	0.06003
ENE	0.03891	0.05314	0.00520	0.00076	0.00000	0.00000	0.09801	0.01626	0.03749	0.00680	0.00165	0.00000	0.00000	0.06220
E	0.02178	0.01596	0.00253	0.00000	0.00000	0.00037	0.04064	0.02043	0.01399	0.00392	0.00000	0.00000	0.00000	0.03834
ESE	0.01375	0.00688	0.00000	0.00000	0.00000	0.00000	0.02063	0.01107	0.00770	0.00000	0.00000	0.00000	0.00000	0.01877
SE	0.00655	0.00266	0.00000	0.00000	0.00000	0.00037	0.00958	0.00447	0.00318	0.00000	0.00000	0.00000	0.00000	0.00765
SSE	0.00969	0.00368	0.00073	0.00037	0.00000	0.00000	0.01447	0.01028	0.00223	0.00224	0.00076	0.00000	0.00000	0.01551
S	0.01113	0.01689	0.00216	0.00000	0.00000	0.00000	0.03018	0.01420	0.01538	0.00270	0.00000	0.00000	0.00000	0.03228
SSW	0.01794	0.07121	0.02186	0.00000	0.00000	0.00000	0.11101	0.02268	0.06206	0.02160	0.00224	0.00078	0.00000	0.10936
SW	0.03382	0.06934	0.03479	0.00144	0.00000	0.00000	0.13939	0.02935	0.08052	0.03092	0.00237	0.00000	0.00000	0.14316
WSW	0.03371	0.07260	0.01689	0.00076	0.00000	0.00000	0.12396	0.02726	0.06730	0.02381	0.00115	0.00000	0.00000	0.11952
W	0.01979	0.07220	0.03010	0.00193	0.00000	0.00000	0.12402	0.02246	0.05246	0.02933	0.00076	0.00000	0.00000	0.10501
WNW	0.01514	0.03295	0.01853	0.00284	0.00000	0.00000	0.06946	0.01431	0.02885	0.02122	0.00155	0.00000	0.00000	0.06593
NW	0.01352	0.02184	0.00831	0.00000	0.00000	0.00000	0.04367	0.01743	0.03522	0.02236	0.00000	0.00000	0.00000	0.07501
NNW	0.00874	0.01790	0.01203	0.00037	0.00000	0.00045	0.03949	0.01163	0.03677	0.01269	0.00083	0.00000	0.00000	0.06192
Total	0.27846	0.52697	0.18289	0.01010	0.00039	0.00119	1.00000	0.24650	0.52410	0.21422	0.01440	0.00078	0.00000	1.00000
	Class C frequency 0.04458							Class D frequency 0.33399						
N	0.01227	0.03159	0.01054	0.00218	0.00000	0.00000	0.05658	0.01134	0.03947	0.01233	0.00078	0.00000	0.00000	0.06392
NNE	0.00980	0.02674	0.00873	0.00054	0.00000	0.00000	0.04581	0.01592	0.03649	0.01141	0.00159	0.00000	0.00000	0.06541
NE	0.01186	0.03378	0.01465	0.00166	0.00000	0.00000	0.06195	0.02317	0.04119	0.00989	0.00049	0.00000	0.00000	0.07474
ENE	0.03285	0.03767	0.00390	0.00384	0.00000	0.00000	0.07826	0.03055	0.05437	0.01459	0.00175	0.00000	0.00000	0.10126
E	0.02593	0.01519	0.00164	0.00052	0.00000	0.00000	0.04328	0.02105	0.01234	0.00098	0.00000	0.00007	0.00000	0.03444
ESE	0.01684	0.00817	0.00000	0.00000	0.00000	0.00000	0.02501	0.01403	0.00364	0.00007	0.00000	0.00000	0.00000	0.01774
SE	0.01176	0.00769	0.00000	0.00000	0.00000	0.00000	0.01945	0.00989	0.00574	0.00021	0.00000	0.00000	0.00000	0.01584
SSE	0.00631	0.00918	0.00158	0.00000	0.00000	0.00000	0.01707	0.01216	0.00912	0.00224	0.00014	0.00000	0.00000	0.02366
S	0.00808	0.02267	0.00335	0.00000	0.00000	0.00000	0.03410	0.01447	0.01962	0.00607	0.00065	0.00000	0.00000	0.04081
SSW	0.00801	0.05529	0.01609	0.00111	0.00054	0.00000	0.08104	0.02734	0.04451	0.01655	0.00255	0.00000	0.00000	0.09095
SW	0.03041	0.08680	0.02257	0.00310	0.00000	0.00000	0.14288	0.03739	0.05062	0.01209	0.00162	0.00028	0.00014	0.10214
WSW	0.03214	0.06748	0.01674	0.00186	0.00000	0.00000	0.11822	0.03529	0.03460	0.01015	0.00272	0.00051	0.00007	0.08334
W	0.01979	0.04125	0.01882	0.00279	0.00000	0.00000	0.08265	0.02737	0.04350	0.01889	0.00201	0.00000	0.00000	0.09177
WNW	0.01738	0.03271	0.01579	0.00275	0.00000	0.00000	0.06863	0.01829	0.03857	0.01588	0.00181	0.00000	0.00000	0.07455
NW	0.01357	0.03517	0.02017	0.00000	0.00057	0.00000	0.06948	0.01753	0.02915	0.01249	0.00037	0.00022	0.00000	0.05976
NNW	0.01429	0.03023	0.01053	0.00058	0.00000	0.00000	0.05563	0.01588	0.03314	0.00946	0.00108	0.00015	0.00000	0.05971
Total	0.27127	0.54160	0.16508	0.02093	0.00111	0.00000	1.00000	0.33165	0.49607	0.15329	0.01755	0.00123	0.00020	1.00004
	Class E frequency 0.2881							Class F frequency 0.23854						
N	0.02250	0.01139	0.00099	0.00008	0.00000	0.00000	0.03496	0.01479	0.00042	0.00000	0.00000	0.00011	0.00022	0.01554
NNE	0.01278	0.00914	0.00150	0.00017	0.00000	0.00000	0.02359	0.01584	0.00010	0.00024	0.00000	0.00000	0.00000	0.01618
NE	0.01626	0.00819	0.00061	0.00000	0.00000	0.00000	0.02506	0.01582	0.00000	0.00000	0.00000	0.00000	0.00000	0.01582
ENE	0.04355	0.02127	0.00122	0.00000	0.00000	0.00000	0.06604	0.03651	0.00268	0.00000	0.00000	0.00000	0.00000	0.03919
E	0.03378	0.00459	0.00017	0.00000	0.00000	0.00000	0.03854	0.05881	0.00010	0.00000	0.00000	0.00000	0.00000	0.05891
ESE	0.01528	0.00240	0.00000	0.00000	0.00000	0.00000	0.01768	0.03339	0.00000	0.00000	0.00000	0.00000	0.00010	0.03349
SE	0.01811	0.00320	0.00032	0.00000	0.00000	0.00000	0.02163	0.01867	0.00010	0.00000	0.00000	0.00000	0.00000	0.01877
SSE	0.02090	0.01010	0.00146	0.00016	0.00000	0.00000	0.03262	0.02029	0.00015	0.00000	0.00000	0.00000	0.00000	0.02044
S	0.03069	0.02700	0.00655	0.00143	0.00000	0.00000	0.06567	0.02967	0.00078	0.00000	0.00000	0.00000	0.00000	0.03045
SSW	0.05250	0.05278	0.01530	0.00177	0.00016	0.00000	0.12251	0.06088	0.00226	0.00011	0.00000	0.00000	0.00000	0.06325
SW	0.09163	0.06151	0.01053	0.00067	0.00008	0.00000	0.16442	0.09926	0.00425	0.00000	0.00000	0.00000	0.00000	0.10351
WSW	0.08408	0.02649	0.00617	0.00123	0.00000	0.00000	0.11797	0.12584	0.00284	0.00000	0.00000	0.00000	0.00000	0.12868
W	0.05896	0.03287	0.00730	0.00046	0.00000	0.00000	0.09959	0.12743	0.00122	0.00000	0.00000	0.00000	0.00000	0.12865
WNW	0.04197	0.02673	0.00582	0.00032	0.00000	0.00000	0.07484	0.14417	0.00020	0.00000	0.00000	0.00000	0.00000	0.14437
NW	0.03663	0.01442	0.00222	0.00016	0.00000	0.00000	0.05343	0.12380	0.00031	0.00000	0.00000	0.00000	0.00000	0.12411
NNW	0.02943	0.01004	0.00174	0.00025	0.00000	0.00000	0.04146	0.05745	0.00120	0.00000	0.00000	0.00000	0.00000	0.05865
Total	0.60905	0.32212	0.06189	0.00670	0.00024	0.00000	1.00000	0.98262	0.01660	0.00035	0.00000	0.00011	0.00032	1.00000

Source: Killough et al. (1993, Table ES-13)

Killough et al. (1993, Appendix E) explored the possibility of using the variability in the Cincinnati Airport data between earlier and later periods to adjust the on-site FEMP data, but concluded that any such adjustment required further study. For the time being, they decided that the 1987–1991 FEMP data constituted the best basis for site-specific assessments. We have adopted these conclusions in the present analysis.

B.2 FEMP Site Geography

We used a map of the FEMP site shown by Killough et al. (1998, Figure 38) as the basis of our model of the locations of the K-65 silos and the potentially occupied areas of the site. A slightly cropped version of this map is shown in Figure B-1. We created a simplified outline of the site, as shown by the red outline which we added to the map. The outline encompasses almost the entire area of the site, with the exception of the northwest corner, which is remote from the radon sources in the K-65 silos, labeled as "Waste Storage Silos" on this map. A detailed view of the silos and the surrounding security fence, excerpted from Killough et al. (1998, Figure 40), is shown in Figure B-2.

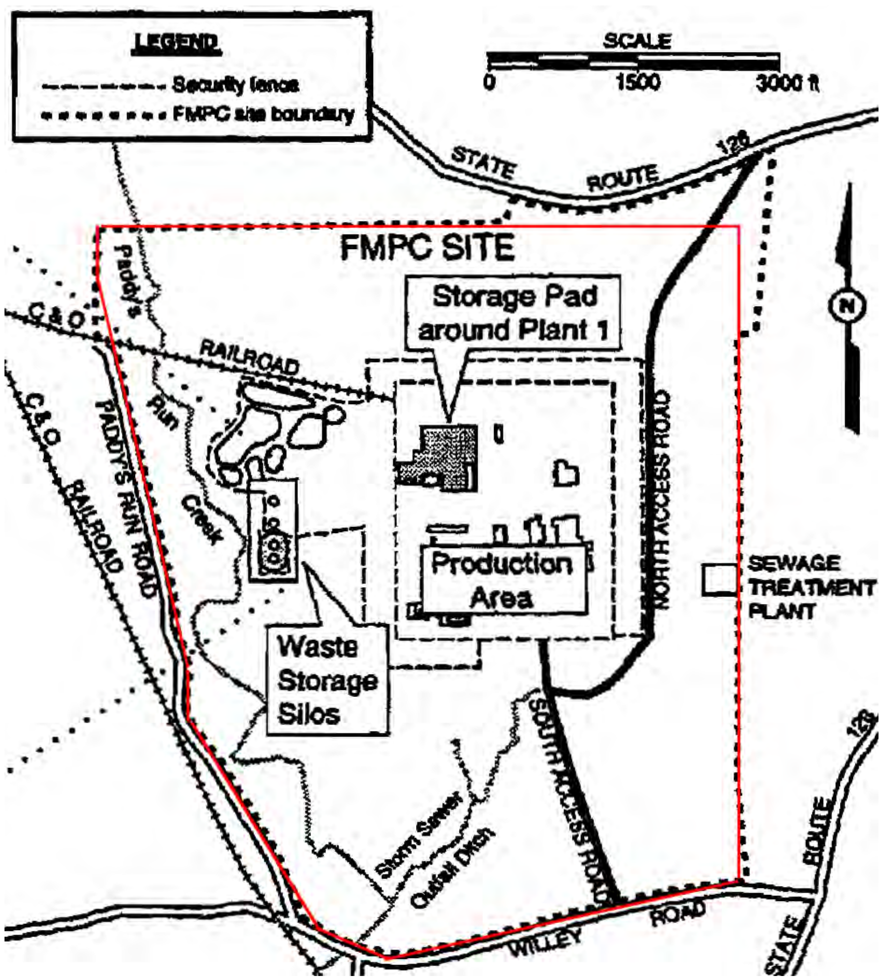

Figure B-1. Map of FEMP Site (Killough et al. 1998, Figure 38), Showing Boundary Used in χ/Q Calculation

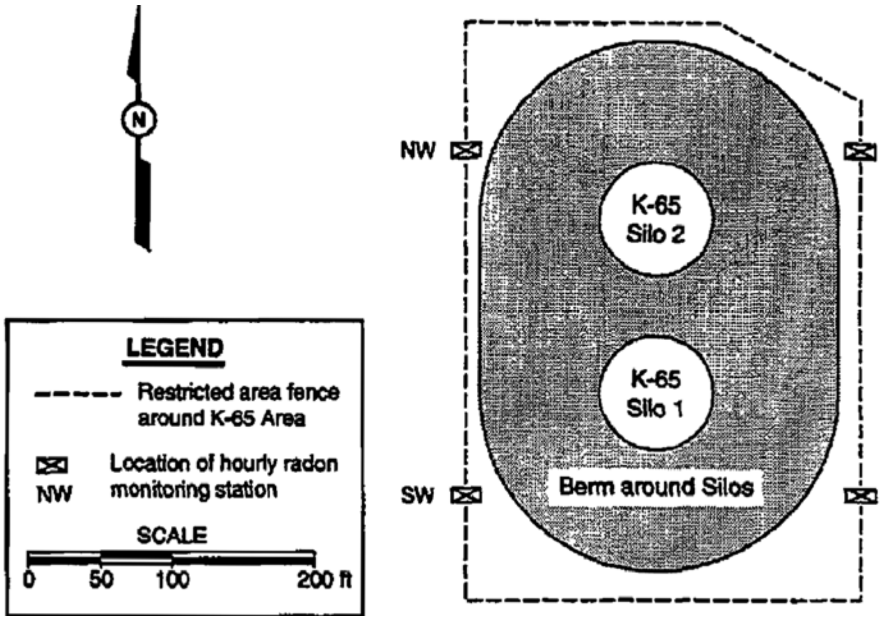

Figure B-2. Map of K-65 Silos (Killough et al. 1998, Figure 40)

As described in Section 2.1.1, the area within the red outline in Figure B-1, but outside the security fence surrounding the silos, was divided into a set of contiguous squares measuring 20 x 20 m. A computer program, which was created for this purpose, was used to calculate the χ/Q at the center of each square for a release point halfway between the two silos, using Equation 4 in the main report and the joint frequency data listed in Table B-1. Figure B-3 shows the outline of the FEMP site used in the χ/Q calculations. The location of the silos is indicated by the reduced-scale image created from Figure B-2. The security fence is shown as a red outline surrounding the silos, while the locations of the 9,586 squares are indicated by the small blue squares. For purposes of illustration, these squares are slightly smaller than if they were drawn to scale; otherwise, they would form a solid blue area.

The actual area of the FEMP site is 1,050 acres, or 4.249 km^2. The area enclosed by the red outline in Figure B-1 is 3.844 km^2, which comprises over 90% of the total area. The missing area is primarily in the northeast corner of the site. Since this area is distant from the K-65 silos, omitting the area, which was done to simplify the computer model, has the effect of slightly increasing the average χ/Q for the site.

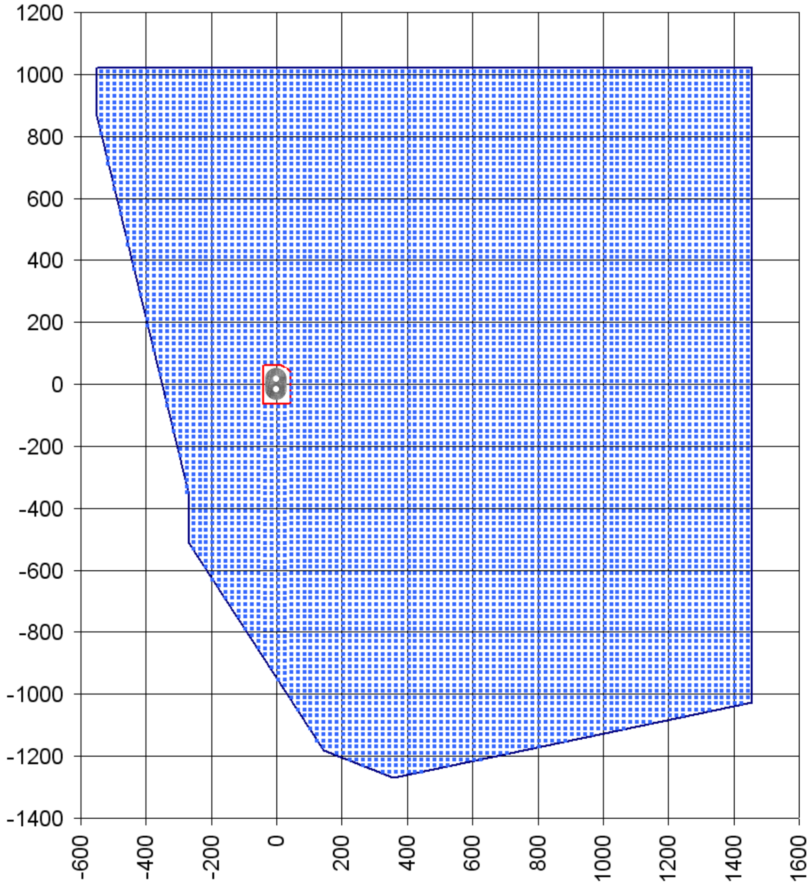

Figure B-3. Outline of FEMP Site, Showing Grid Used for χ/Q Calculation and Location of K-65 Silos (grid scale in meters)

References for Appendix B

Environmental Protection Agency (U.S.)(EPA). 1992. CAP88-PC: Clean Air Assessment Package, Ver. 1, CCC-542 C. RSICC Computer Code Collection [Computer software and manual]. Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Killough, G. G., et al. 1993. "The Fernald Dosimetry Reconstruction Project, Task 4: Environmental Pathways—Models and Validation," RAC Report No. CDC-3. Neeses, South Carolina: Radiological Assessments Corporation.

Killough, G. G., et al. 1998. "The Fernald Dosimetry Reconstruction Project, Task 6: Radiation Doses and Risk to Residents from FMPC Operations from 1951-1988," Vol. 1, RAC Report No. 1-CDC-Fernald-1998-Final (Vol. 1). Neeses, South Carolina: Radiological Assessments Corporation.