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REVISED SILO 1 AND 2 REMOVAL ACTION BENTONITE EFFECTIVENESS ENVIRONMENTAL MONITORING PLAN

3-17-92

DOE/EPA
DOE-1015-92
2
~~LETTER~~ plan

R-008-106.3

Department of Energy
Fernald Environmental Management Project
P.O. Box 398705
Cincinnati, Ohio 45239-8705
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3030

MAR 17 1992

DOE-1015-92

Mr. James A. Saric, Remedial Project Director
U. S. Environmental Protection Agency
Region V - 5HRE-8J
77 W. Jackson Boulevard
Chicago, Illinois 60604

Mr. Graham E. Mitchell, Project Manager
Ohio Environmental Protection Agency
40 South Main Street
Dayton, Ohio 45402-2086

Dear Mr. Saric and Mr. Mitchell:

REVISED SILO 1 AND 2 REMOVAL ACTION BENTONITE EFFECTIVENESS ENVIRONMENTAL MONITORING PLAN

Enclosed for your approval is the Revised Silo 1 and 2 Removal Action Bentonite Effectiveness Environmental Monitoring Plan. To facilitate your review, I have enclosed the information you requested on the Borak method, as well as the other site specific referenced documents.

Because results utilizing the model are due to you in April 1992, your expedited approval of the plan is requested.

If you or your staff have any questions, please contact Randi Allen at FTS 774-6158 or (513) 738-6158.

Sincerely,

Jack R. Craig
Fernald Remedial Action
Project Manager

FN:Allen

Enclosures: As Stated

Recycled and Recyclable

cc w/enc.:

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Silos 1 and 2 Removal Action [redacted]

Bentonite Effectiveness

Environmental Monitoring Plan

March 13, 1992

Continuous (i.e., real time) and integrated (i.e., passive) sampling for ^{222}Rn is being performed as part of the routine environmental monitoring program at the Fernald Environmental Management Project (FEMP). The recent removal action involving application of a bentonite sealant layer to the K-65 silos is expected to produce a reduction in the quantity of ^{222}Rn being emitted from the silos. Continuous measurements of ^{222}Rn in the head space of the K-65 silos will be utilized with a Gaussian plume model computer program and site specific meteorological data to determine what contribution residual radon emissions from the K-65 silos make to the offsite background radon concentration.

One of the objectives of the environmental ^{222}Rn monitoring and analysis at the FEMP is to determine whether ^{222}Rn emitted from the K-65 silos following the bentonite sealant application has been reduced to a level such that its contribution to offsite background is less than 0.015 pCi/l at the location of the maximally exposed individual at a non-FEMP location. Because the measured annual average offsite environmental radon background concentration is 0.5 ± 0.1 pCi/l, contributions to the radon background concentration equal to 0.015 pCi/l can be determined only by modeling since monitoring techniques are not sufficiently precise to reliably detect such a small change.

The Gaussian plume model computer code adopted by FEMP can predict what contribution to the offsite radon background is being produced from radon emitted by the K-65 silos. The flux of radon ($pCi/M^2/sec$) which is emitted from the silo dome by mechanisms of diffusion and air exchange (ventilation) will be used as the source term for the Gaussian plume model. This flux will be calculated from the measured concentration of radon (pCi/M^3) in the dome headspace.

Two pathways for emissions of ^{222}Rn from the silos are considered: (1) diffusion of ^{222}Rn in the K-65 silo air through the concrete dome and polyurethane foam and (2) free air exchange between the silo air and the surrounding air (ventilation).

Diffusion Releases

The calculations by Borak (1985) of diffusion releases of ^{222}Rn were based on one dimensional steady-state diffusion equations obtained from an National Bureau of Standards (NBS) summary technical report (Colle' et al. 1981).

[redacted]

From the concentration of ^{222}Rn in the silo air, the flux of ^{222}Rn diffusion through the concrete dome can be calculated by:

$$J_c = \frac{E_c \lambda_{Rn} l_c C_a}{\sinh\left(\frac{L}{l_c}\right)}$$

Where:

J_c = ^{222}Rn flux from the concrete dome surfaces to the foam (pCi/M²/sec, or similar units),
E_c = total porosity of the dome concrete - (0.3),
l_c = diffusion length of ^{222}Rn in the dome concrete - (12 cm)
L = thickness of the dome concrete - (10 cm)
λ_{Rn} = decay constant of ^{222}Rn - (2.1×10^{-6} s^{-1}),
C_a = concentration of ^{222}Rn in the silo air,

There is a foam and polyurethane coating over the surface of the concrete dome on each silo. This layer is an effective radon barrier based on the laboratory measured diffusion coefficient of 4×10^{-6} $cm^2 - s^{-1}$ (TIM-8700/1). This foam layer will further attenuate the radon flux before the radon is emitted to the atmosphere. This attenuation is determined as follows:

$$J = J_c \exp\left(\frac{-L_f}{\sqrt{D_f/\lambda_{Rn}}}\right)$$

Where:

J = ^{222}Rn flux emitted to the surrounding air (pCi/m²-s)

Jc = ^{222}Rn flux emitted from concrete surface of the dome into the foam

L_f = thickness of the foam (10 cm)

D_f = diffusion coefficient for the foam (4×10^{-6} cm^2/s)

The total release rate is then the product of the ^{222}Rn flux and the surface area of the dome. $Q_{diff} = JA$ where A equals the area of the dome.

Free Air Exchange (Ventilation)

Ventilation of radon from the silo is governed by the physics associated with the ideal gas law and, as such, is dependent upon the temperature and pressure changes of the gases in the silo headspace as a result in the changes in the ambient atmosphere. The calculation of emissions of ^{222}Rn due to ventilation from the silos is based on the expansion of the silo gases due to changes in atmospheric conditions. The ventilation of silo gases is determined from the ideal gas law using temperature and pressure data collected.

[redacted]

[redacted]

$$PV = nRT$$

Where:

P = pressure of the gases within the silo,
V = volume of the silo,
n = number of moles of the gases,
R = ideal gas constant, with appropriate units, and
T = temperature, in units of an absolute scale (K or °R).

The silo gases' internal temperature and pressure has been collected and continues to be collected. This data is used to determine the release of radon due to the ventilation of silo gases.

For air exchange emissions, the assumption is made that the ^{222}Rn concentration in outside air is negligible compared to the silo concentration so that outside air does not provide a source of ^{222}Rn to the silo air. The ventilation of radon to the atmosphere is assumed to be small compared to the production of radon gases, thus the concentration of radon in the silos is assumed to be a constant which does not deviate from equilibrium. With these assumptions, the basic equation describing the rate of change in the silo air ^{222}Rn concentration can be written (NCRP 1989):

$$\frac{dC_a}{dt} = \frac{P_{Rn}}{V_0} - C_a \lambda_{eff}$$

Where:

C_a = concentration of $_{222}Rn$ in the silo air,
P_{Rn} = the constrained (by the presence of the silo) rate of release of $_{222}Rn$ into the silo air (production term) from the K-65 source material (activity per time),
V_o = volume of the air space in the silo above the K-65 material,
λ_{eff} = the effective removal rate of $_{222}Rn$ = $\lambda_{Eff} = \lambda_{Rn} + \lambda_v$,
λ_{Rn} = decay constant of ^{222}Rn - ($2.1 \times 10^{-6}\ s^{-1}$),
λ_v = The ventilation rate due to the daily atmospheric changes $\lambda_{v,\Delta T}$ is the fraction of the silo air exhaled due to the atmospheric changes per some unit of time period, with the units of air changes per time. Therefore:

$$\lambda_v = \Delta n / n_0$$

where we define:

Δn = the change of number of moles of gas in silo headspace,
n_0 = the initial number of moles of gas in silo headspace

[redacted]

[redacted]

Based on the assumption of equilibrium of the radon in the headspace the following relationship is obtained:

$$P_{Rn} = C_a \lambda_{eff} V_o$$

Because the silo air space is a single compartment volume, it is assumed that the contained air will be well mixed. Thus, the air exchange release rate is simply the activity in the silo air space times the silo ventilation rate:

$$Q_{exch} = C_a \lambda_v V_o$$

where Q_{exch} is the rate of release of ^{222}Rn from the silo through air exchange.

The radon release rate from the diffusion process and air exchange process ($Q_{total} = Q_{diff} + Q_{exch}$) is then used as the source term input into the ISC model program. Both mechanisms of diffusion and air exchange (ventilation) will be considered in converting radon concentrations in the dome headspace to the radon release rate.

Periodic analysis of the predicted and measured offsite radon background concentration will provide information to determine the gross effectiveness of the model. Data collected from the silo headspace radon monitor will determine the relative integrity of the bentonite unrelated to changes in meteorological parameters.

The Gaussian plume model computer code, ISC version #3.4, December 1988, is currently being used to calculate what contribution ^{222}Rn emitted from the K-65 silos makes to the offsite background radon concentration. ISC is composed of two programs designed to predict the atmospheric dispersion of air emissions: ISC Short Term for predicting concentration over 1, 2, . . ., 24 hour periods and ISC Long Term for calculating quarterly, seasonal, or annual concentration. The radon monitoring data being collected at FEMP is best analyzed using ISC Long Term. Although a new version of ISC Short Term is currently available for testing, ISC Short Term will not be implemented at this time for these analyses.

Site-specific meteorological parameters and the calculated ^{222}Rn release rates are used as input to the ISC Gaussian plume model computer code to predict the radon concentration at any predetermined location relative to the K-65 silos as the source of ^{222}Rn. Predictions of the Gaussian plume model will be compared to results of actual ^{222}Rn monitoring data, although the contribution of ^{222}Rn from the K-65 silo to offsite ^{222}Rn background is expected to be very small and may not be measurable at the site boundary unless there is an unexpected release of radon due to a failure of the bentonite sealant.

The annual average offsite ^{222}Rn background is approximately 0.5 pCi/l ± 0.1 pCi/l. Therefore, it is not possible to confirm by measurements whether ^{222}Rn emitted from the K-65 silos increases the offsite radon background in excess of 0.015 pCi/l for the maximally exposed individual. However, the ISC computer model calculations, which use as a source term the ^{222}Rn concentration actually measured in the headspace of the K-65 silos, will predict how much of the offsite ^{222}Rn background is due to ^{222}Rn emissions from the K-65 silos.

[redacted] 6

Real-time ^{222}Rn monitoring data, including measurement of ^{222}Rn in the K-65 silo headspace, will be generated and recorded hourly. Permanent files of the hourly data are available on computer discs. Data from integrated radon measurements are available on a quarterly basis since samples are collected for a three month period. For a fixed location, variations in the radon concentration are due, primarily, to changes in meteorological parameters which impact the amount of mixing and dilution experienced by the ^{222}Rn emitted from the K-65 silos. Likewise, periodic changes in ^{222}Rn flux from the K-65 silos are due to diurnal changes in certain meteorological parameters, such as, barometric pressure, wind speed, temperature and solar radiation.

Evaluation of the predicted contribution to offsite radon background, using the ISC Gaussian plume model computer code with values of the radon release rate calculated from actual headspace concentration measurements in the K-65 silos and site-specific meteorological parameters, will be accomplished by comparing the model's predictions to the actual measured results of offsite radon background using both continuous and integrated samplers. This evaluation will be performed to determine compliance with the 0.015 pCi/l limit and to provide a gross independent assessment of the model accuracy.

The Gaussian plume computer model will use hourly measurements of the radon concentration in the headspace of the K-65 silos along with site-specific meteorological parameters to predict radon concentration at any location. Sets of data will be generated to produce a weekly average concentration for all offsite monitoring locations. Analysis of the average weekly predicted radon background concentration and the actual measured average values will be reported. Although field monitoring techniques do not have the precision to detect a variation in the offsite background ^{222}Rn concentration of 0.015 pCi/l, the computer model, which uses measurements of ^{222}Rn in the K-65 silo dome headspace to predict the actual contribution to offsite ^{222}Rn background, is adequately precise to calculate these values.

REFERENCES

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Colle', R; Rubin, R. J.; Knab, L. I.; Hutchinson, J. M. R. Radon transport through and exhalation from building materials: a review and assessment. Washington, DC: National Bureau of Standards, U.S. Department of Commerce; NBS Technical Note 1139; 1981

NCRP (National Council on Radiation Protection and Measurements). Control of radon in houses. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Report No. 103; 1989

✓Radiological Assessments Corporation, The Fernald Dosimetry Reconstruction Project, Tasks 2 and 3: Radionuclide Source Terms and Uncertainties - 1960 - 1962 (Draft), Submitted to the Centers for Disease Control in Partial Fulfillment of Contract No. 200-90-0803, December, 1991

✓Nielson, K. K., Rogers, V. C., Radon Diffusion Coefficient Measurements of Polyurethane Materials and Radon Attenuation Calculation for K-65 Silos, Technical Information Memorandum, TIM-8700/1; October 13, 1987

APPENDIX J

RELEASES OF RADON FROM K-65 SILOS

INTRODUCTION

This appendix provides detailed descriptions of the estimates of ^{222}Rn releases from the K-65 Silos. First, however, we present characteristics of and general information about the K-65 Silos and material. Since the current estimates of releases utilize the same general methods for air exchange and diffusion releases as the previous estimates, we next describe the previous estimates. Then we discuss the current estimates of releases of ^{222}Rn and daughters that have been developed in the Fernald Dosimetry Reconstruction Project, including the models used, the distributions chosen to represent parameter uncertainties, the mechanics of the calculations, and the results.

CHARACTERISTICS OF K-65 SILOS AND K-65 MATERIAL

For reasons discussed later in this appendix (see page J-9) the current estimates of ^{222}Rn releases have considered the K-65 Silos, Silos 1 and 2, to be the only significant sources of Rn releases. The previous estimates of ^{222}Rn source terms from the FMPC have also considered the K-65 Silos to be the only sources. Thus, the characterization information in this section focuses primarily on the K-65 Silos.

Facility Description

Four large concrete storage tanks, called silos, are located in the waste disposal area of the FMPC (see Figure 2 in the main report). These silos are in a north-south line, and are about 1000 ft west of the production area. The silos are numbered one to four, with the southernmost silo being Silo 1. Silos 1 and 2 contain K-65 waste material from the extraction processing of uranium ore, and are thus referred to as the K-65 Silos (DOE 1990). The K-65 material contains very high concentrations of ^{226}Ra (DOE 1990), and has long been known as a significant source of ^{222}Rn (Strattman 1955; Boback 1979; and others). Radon-222 is formed from the decay of ^{226}Ra. Silo 3, the Metal Oxide Silo, contains the metal oxide waste material from the extraction processing of uranium ores and concentrates. The metal oxide material is also contaminated with radioactivity, but the concentration of ^{226}Ra is much lower than in the K-65 material. Silo 4 has never been used, and contains only water with very low levels of radioactive and chemical contaminants (DOE 1990).

As shown in Figure J-1, each silo is 80 ft in diameter with an overall height of 36 ft, of which about 26 ft 8 in is the tank wall and about 9 ft 4 in is the domed roof of the silo (Preload 1951a; Shanks and Vogel 1988). The walls are 8 inch thick concrete and the domes are 4 inch thick concrete (Preload 1951a; Shanks and Vogel 1988). The K-65 material occupies roughly two thirds of the silos' full volumes of about 160,000 ft^3 (4500 m^3).

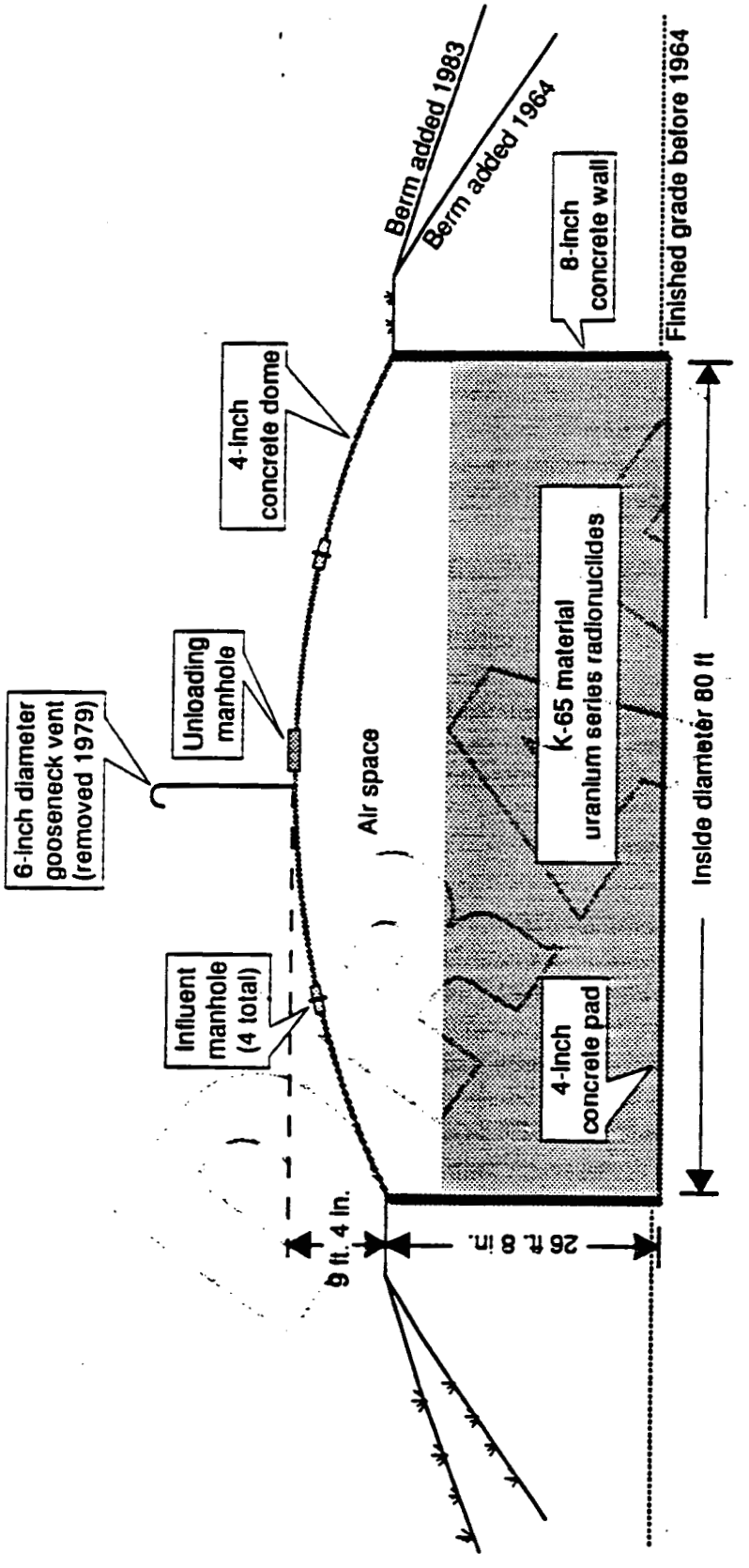

Figure J-1. K-65 Silo cross section.

Disposal History

The K-65 Silos were constructed in 1951 to 1952 for the temporary storage of K-65 materials (Grumski 1987; Shanks and Vogel 1988). Originally the K-65 residues were to be returned to the African Metals Corporation, which provided the pitchblende ore, called Q-11, processed for its high uranium content. The K-65 residue is one particular waste product from the extraction of uranium from pitchblende ores, and contains high concentrations of ^{226}Ra, gold, and other metals.

The FMPC-2082 report indicated that K-65 materials were added to the silos from 1953 until 1955 (Boback et al. 1987). Additional documentation about the history of disposal of K-65 at the FMPC has been obtained. This information is summarized in Table J-1 and indicates K-65 materials were added to the silos from July 1952 through September 1958.

Table J-1. Disposal History of the K-65 Silos

Date(s)	Activities (reference)
1951–1952	Construction of the silos (Grumski 1987; Shanks and Vogel 1988).
Sep 1951	Shipping of drummed K-65 from Mallinckrodt Chemical Works (MCW) in St. Louis began (Blythe 1951; Walden 1952).
Jul 1952	Disposal of MCW-generated, drummed K-65 material, by slurrying to Silos, began (Davis 1952).
About Jun 1953	The south silo, Silo 1, was full, and storage of material in Silo 2 had begun (derived from Strattman 1953).
Oct 1955 to Jan 1956	Campaign 1 of FMPC Q-11 processing and K-65 production and disposal (Lynch circa 1958).
Nov 1955	Drummed K-65 continued to arrive from MCW, and was still being added to silo (Madoffori 1955a; Madoffori 1955b; Madoffori 1955c).
Aug to Oct 1956	Campaign 2 of FMPC Q-11 processing and K-65 production and disposal (Lynch circa 1958).
Mar to Apr 1957	Campaign 3 of FMPC Q-11 processing and K-65 production and disposal (Lynch circa 1958).
May 1957	Campaign 4 of FMPC Q-11 processing and K-65 production and disposal (Lynch circa 1958).
Sep 1957	Campaign 5 of FMPC Q-11 processing and K-65 production and disposal (Lynch circa 1958).
Dec 1957	Campaign 6 of FMPC Q-11 processing and K-65 production and disposal (Lynch circa 1958).
Mar 1958	Campaign 7 of FMPC Q-11 processing and K-65 production and disposal (Lynch circa 1958).
Jun to Sep 1958	Campaign 8 of FMPC Q-11 processing and K-65 production and disposal (Lynch circa 1958).
Sep 1958	The north silo, Silo 2, was removed from service and decanted (Noyes 1958).

History of Silo Structural Characteristics Affecting Rn Releases

The K-65 Silos have had problems of deterioration, almost since the time of construction. Significant cracking in the walls and seepage of the contents was noted from the 1950s (Wunder 1954; Martin 1957). Because of these problems, repairs and improvements to the Silos have occurred from the 1960s through the 1980s. The significant changes to the Silos are summarized in Table J-2.

Table J-2. Summary of Historical Changes to the K-65 Storage Silos

Date	Repairs or Improvements (reference)
1964	Cracks in silo walls were patched, waterproofing sealant applied, and earthen berm constructed to counterbalance material inside silos (Shanks and Vogel 1988; Noyes 1964).
1979	Openings in silo domes, including the gooseneck pipe and other penetrations, were sealed, with gaskets installed, to prevent Rn emissions (Boback 1980; Grumski 1987).
1983	The earthen berms were enlarged to correct erosion problems (Grumski 1987; Shanks and Vogel 1988).
Early 1986	Dome covers added to protect the center sections of the silo domes; neoprene membrane layer applied to part of Silo 2 (Grumski 1987; Shanks and Vogel 1988).
Nov 1987	Radon Treatment System installed to treat displaced Rn during work on Silos (not continuously operated) (Grumski and Shanks 1988; Shanks and Vogel 1988).
Dec 1987	Rigid, polyurethane foam layer and urethane coating applied to exterior of silo dome surfaces to weatherproof the Silos (Grumski and Shanks 1988; Shanks and Vogel 1988).

Characteristics of K-65 Material

Various characterization studies have been undertaken on the K-65 materials in the past. Currently, the K-65 Silos are included as Operable Unit 4 in the FMPC Remedial Investigation and Feasibility Study (RI/FS) of the Department of Energy. A summary of the results of these studies for some parameters pertinent to estimates of ^{222}Rn generation rates is given in Table J-3.

As seen in the range of ^{226}Ra concentrations found in the recent sampling of the silos (DOE 1990), the K-65 material is not homogeneous. The color of the material also varied greatly.

The range of moisture contents reported for the recent DOE sampling is a summary of eight measurements (DOE 1990). Of the eight, five were between about 20 and about 35%, one was roughly 50%, and two were between 70 and 75%. It seems likely that the two highest values were for saturated material. We note that the DOE report did not indicate the vertical location in the silos from which the material was sampled. In fact, because the sample cores generally had very low recoveries (fraction of the sampled material retained in

the sampling device), mostly from 4 to 30%, the vertical locations can probably not be determined. Thus, no information about the vertical profile of moisture content in the K-65 material can be discerned from this recent data.

Table J-3. Characteristics of K-65 Material

Time of study	Concentration ^{226}Ra [a]	Moisture content (dry weight %)	Density (g cm^{-3})	Comments
1952	0.3 ppm	30[b]	1.179	Earlier study reported by DOE (1990)
1972	0.28 and 0.36 ppm	62 and 68[c]	0.87–1.18[d]	Earlier study reported by DOE (1990)
1980	0.2 ppm	—	—	Earlier study reported by DOE (1990)
1988	0.13–0.21 ppm	—	—	Earlier work reported by DOE (1990)
1989	657–192,600 pCi g^{-1}; mean 110,000 pCi g^{-1}; geometric mean 76,000 pCi g^{-1}; geometric standard deviation 4.4	21.8–73.5[b]	—	RI/FS sampling effort (DOE 1990)

[a] Concentrations are presented in the units given in the reference. For conversion between units for ^{226}Ra concentrations, 1 ppm = 0.988 µCi g^{-1}.

[b] The basis of the unit (%) was not given in the reference, but is assumed to be dry weight.

[c] The values of water content for these samples were calculated, in this present work, from average concentrations of uranium on an as received (wet) basis and on a dry basis. These concentrations were obtained from a laboratory analytical data sheet (NLCO 1972) for samples reported by Nelson (1972b).

[d] These densities were reported by Nelson (1972b). Three values were reported; a value of 60 lb ft^{-3} for both silos was attributed to Cotter Corporation, and values of 54.3 and 73.7 lb ft^{-3} for Silo 1 and Silo 2, respectively, were attributed to NLO.

We note that the densities measured in the early studies seem anomalously low, when compared to typical values for uranium mill tailings or soils. The letter report by Nelson (1972b) does not indicate the method of determining the densities. Usually one would assume the values to be dry bulk densities. However, in the report (Nelson 1972b) the densities were used, in a calculation of the total weight of U in the silos, as if they were "as received," or wet, densities. If the reported densities were wet bulk densities, with moisture content around 65% dry weight (as reported by NLCO (1972) for the same samples), the dry

bulk densities would be about 0.5 to 0.7 g cm^{-3}, which seem incredibly low. No results of bulk density measurements were reported in the recent RI/FS sampling (DOE 1990).

No specific values were reported for the porosity of the K-65 material. However, the recent sampling (DOE 1990) did report values for the specific gravity of eight samples to be between 2.58 and 3.37. Using the range of densities reported in the early studies (assumed to be dry bulk densities) would result in relatively high (compared to typical uranium mill tailings) estimates of porosity from about 0.54 to 0.74. Information searches and discussions with the RI/FS Operable Unit 4 staff have indicated that measurements of ^{222}Rn emanation fraction from and diffusion coefficient in the K-65 material have not been performed.

EVALUATION OF PREVIOUS ESTIMATES OF RADON RELEASES FROM K-65 SILOS

The source term for ^{222}Rn emissions from the K-65 storage silos was previously evaluated by IT Corporation, in their assessment of doses from historical releases from the FMPC (IT 1989). This assessment by IT Corporation did not include original calculations, rather it summarized calculations from two other sources. Two pathways for emissions of Rn from the silos were considered: (1) diffusion of Rn from the K-65 residue into the silo air space and subsequent diffusion through the concrete domes into the surrounding air, and (2) free air exchange between the silo air and surrounding air, through cracks in the domes. The estimate of diffusion emissions was taken directly from the calculations of Borak (Borak 1985). It is noted that the FMPC-2082 report estimated the Rn emissions from only the diffusion pathway, and incorporated the Borak report as Appendix A (Boback et al. 1987). In the IT report, the estimate of air exchange emissions was taken from a WMCO feasibility investigation report, with minor modification (Grumski 1987; IT 1989). Detailed descriptions of these previous assessments of Rn releases from the K-65 Silos follow.

Diffusion Releases

The calculations by Borak (1985) of diffusion releases of ^{222}Rn were based on one-dimensional steady-state diffusion equations obtained from an NBS summary technical report (Collé et al. 1981). The concentration of ^{222}Rn in the silo air space was first calculated from characteristics of the K-65 waste material and dimensions of the silos:

$$C_a = \frac{\phi}{\lambda_{Rn}} \left(\frac{E_w l_w}{E_w l_w + h} \right) \qquad \text{(J-1)}$$

where:

C_a = concentration of ^{222}Rn in the silo air,
ϕ = production source term of ^{222}Rn in pores of K-65 material,
λ_{Rn} = decay constant of ^{222}Rn,
E_w = total porosity of the K-65 waste material,
l_w = diffusion length of ^{222}Rn in the K-65 waste material, and
h = height of the air space in the silos above the waste material.

The production source term of ^{222}Rn in pore spaces was determined by:

$$\phi = \frac{[Ra]EF\, p_w \lambda_{Rn}}{E_w} \qquad \text{(J-2)}$$

where:

[Ra] = concentration of ^{226}Ra in K-65 waste material (activity per mass),
EF = emanation fraction of ^{222}Rn production in K-65 material, and
p_w = bulk density of K-65 waste material.

From the concentration of ^{222}Rn in the silo air, the flux of ^{222}Rn diffusion through the concrete dome was calculated by:

$$J = \frac{E_c \lambda_{Rn} l_c C_a}{\sinh\left(\frac{L}{l_c}\right)} \qquad \text{(J-3)}$$

where

J = ^{222}Rn flux from the dome surfaces to the surrounding air (pCi m^{-2} s^{-1}, or similar units),
E_c = total porosity of the dome concrete,
l_c = diffusion length of ^{222}Rn in the dome concrete, and
L = thickness of the dome concrete.

The total release rate is then the product of the ^{222}Rn flux and the surface area of the domes. It was assumed that the domes approximate circles of 40 ft radii, and thus the surface area of each dome is about 5030 ft^2, or 467 m^2.

The parameter values used by Borak are given in Table J-4. However, we note that the sources of these values were not documented (Borak 1985). The results of these diffusion release calculations were a ^{222}Rn concentration in the silo air of 3×10^7 pCi L^{-1}, and a total release rate to the atmosphere of 60 Ci y^{-1} (Borak 1985).

Table J-4. Input Parameter Values Used in the Previous Assessment of Diffusion Releases[a]

Parameter (units)	Value used
λ_{Rn} (s^{-1})	2.1×10^{-6}
E_w	0.3
l_w (cm)	150
h (cm)	300
[Ra] (pCi g^{-1})	2×10^5
EF	0.2
p_w (g cm^{-3})	1.6
E_c	0.3
l_c (cm)	12
L (cm)	10

[a] Ref: Borak 1985.

[redacted]

Free air exchange

As part of the investigations of the K-65 silos for controlling ^{222}Rn emissions, the FMPC performed temperature and pressure monitoring of the silos. Measurements of temperature at two depths into the silo air space, on the surface of the concrete domes, and in ambient air near the silos, and measurements of differential pressure between the silo air space and the atmosphere were obtained from March 13 to May 15, 1987 (Grumski 1987). Due to instrument problems, much of the data was not usable. However, usable data were obtained for 11 complete days, including a three-day period, May 8 to 11, during which the daily increases in temperature were large (Grumski 1987; Shanks 1991).

For this three-day period, the internal gas temperatures for both silos showed a maximum daily increase of about 35 °F. Using the Ideal Gas Law, it was estimated that a closed tank of air initially at a pressure of 2117 PSF (14.7 psi) and temperature of 63 °F would undergo an internal pressure increase of about 142 PSF (pounds ft^{-2}) if the internal temperature was increased 35 °F (Grumski 1987). For this monitoring period, the pressure monitoring indicated that Silo 2 held a maximum positive differential pressure of 7.6 PSF and a maximum negative pressure of 4.9 PSF. The maximum differential pressure was about 5% of what would be expected for a sealed system. Silo 1 showed negligible differential pressure with these temperature variations. It was concluded that the silos can not hold any significant pressure and thus that increases in the temperature of the internal silo air resulted in the volumetric expansion of the air and the release of "excess" volume to the atmosphere (Grumski 1987).

The calculation of free air exchange emissions of ^{222}Rn from the silos was based on the expansion of the silo gases with warming of the gases due to warming of exterior air. The Ideal Gas Law was used to calculate the volume of air that would be emitted from the silos (Grumski 1987):

$$PV = nRT \qquad \text{(J - 4)}$$

where

P = pressure of the gases within the silo,
V = volume of the silo,
n = number of atoms of the gases,
R = ideal gas constant, with appropriate units, and
T = temperature, in units of an absolute scale (K or °R).

The calculations (Grumski 1987) assumed that the internal gas pressure does not change. If this is the case, the volume of a given quantity of gas will be directly proportional to the temperature of the gas. Thus, the change in volume for a temperature change was calculated as:

$$\Delta V = (\Delta T / T_0) V_0 \qquad \text{(J - 5)}$$

where

ΔV = change in volume per day,
ΔT = change in temperature per day,
T_0 = the initial temperature, and
V_0 = the initial volume.

It was then assumed that, in the case of rising temperatures during a typical day, the complete increase in volume, ΔV, is released from the silo to the surrounding air. In this case the ^{222}Rn released, Q, is simply calculated as:

$$Q = C_a \Delta V \qquad \text{(J - 6)}$$

For this calculation, the ^{222}Rn concentration used was the value of 3×10^7 pCi L^{-1} calculated earlier by Borak (Grumski 1987; IT 1989). The value used for ΔV was 1000 ft^3 d^{-1}, based on a value of ΔT of 20°F d^{-1}. The first calculations in the feasibility study used a silo air volume of 25,000 ft^3 (Grumski 1987). This resulted in a calculated release rate of 600 Ci y^{-1}, for the two silos combined. The sources of the parameters used were not documented (Grumski 1987).

However, the silo volume was revised to 43,758 ft^3 in the IT dose assessment (IT 1989). This increased the estimated release rate to 512 Ci y^{-1} for each silo, or a total of 1023 Ci y^{-1} (IT 1989).

CURRENT ESTIMATES OF RADON RELEASES FROM K-65 SILOS

In this section we discuss the general methodology used in the current estimates of ^{222}Rn releases, followed by a justification of the specific approaches to calculating releases through air exchange. Then, we thoroughly discuss the equations (models) used for the calculations, along with the distributions chosen to represent the uncertainty of the parameters. We then provide additional information about details of the mechanics of the calculations, and finally we present the results of the analysis.

General Methodology for Current Release Estimates

For this preliminary assessment of the ^{222}Rn source term from the waste storage area, the K-65 Silos, Silos 1 and 2, will be considered the only significant sources of Rn releases. Recent sampling of the K-65 Silos and the Metal Oxide Silo has measured the concentrations of ^{226}Ra. The average concentrations of ^{226}Ra were determined to be about 110,000 pCi g^{-1} in the K-65 Silos, and about 2900 pCi g^{-1} in the Metal Oxide Silo (DOE 1990). Earlier sampling of the K-65 Silos had indicated concentrations of ^{226}Ra averaging about 350,000 pCi g^{-1} (Litz 1974). From these measurements, the concentration of ^{226}Ra appears to be at least 40 times higher in the K-65 Silos than in the Metal Oxide Silo. Thus, a rough estimate is that the K-65 Silos have the potential for generating about 40 times more ^{222}Rn (per silo) than the Metal Oxide Silo. Thus, for this preliminary assessment, the Metal Oxide Silo, Silo 3, is considered an insignificant contributor to the ^{222}Rn releases. Since Silo 4 is essentially empty, it is also not considered a source of Rn releases. The rest of this section will only discuss releases from the K-65 Silos, Silos 1 and 2.

Earlier in this appendix (see page J-4), the history of structural changes to the silos was discussed. Not all of these changes to the silos would have a significant effect on the release of Rn. The most important change, in terms of Rn emissions, was the sealing of the openings in the silos in 1979. This action would have changed the ventilation rate of the silos, and thus changed the rate of ^{222}Rn release. The addition of the exterior foam layer in 1987 may

have further reduced the emission of Rn. This foam layer was found, through laboratory testing, to have a very low Rn diffusion coefficient, which would make it quite effective in reducing the emission of Rn (Grumski and Shanks 1988). The addition of the earthen berms in 1964 could have slightly changed the releases of Rn through the walls of the silos, although specific information regarding this has not been found.

For the current calculation, we assumed that a major change to ^{222}Rn releases likely occurred with the sealing of penetrations in 1979. We also assume that significant changes occurred at the end of 1958, when Silo 2 was decanted and removed from service, and in 1987, when the foam layer was added to the silo domes. However, at this time, we do not need to perform calculations of releases for the periods prior to 1959 or after 1987. Thus, for these calculations, we evaluated two time periods; from 1959 to 1979 and from 1980 to 1987. We use the subscripts "pre" and "post" in variable names, to refer to these two periods, respectively.

The general methods used to estimate the diffusion and free air exchange releases of Rn in the previous assessments are thought to be adequate. However, there are two significant flaws in the previous estimates of diffusion and free air exchange releases of Rn from the K-65 Silos. First, the sources of many of the parameter values used are not documented in the assessment reports (Borak 1985; Boback et al. 1987; Grumski 1987; IT 1989). Thus, it is not possible to track the parameter values back to measurements or calculations in a primary reference. Second, the IT calculations assumed that the same release rate existed from 1953 through 1984 (IT 1989). Since it is known that openings in the silos, including the six-inch diameter gooseneck pipe, were sealed in 1979 (Boback 1980; Grumski 1987), it seems more reasonable to assume that a major change in release rates also occurred when these openings were sealed.

Thus the approach of the current estimates was to use the same basic calculational methods for air exchange and diffusion releases of the previous assessments (Borak 1985; IT 1989), but with changes to best incorporate the additional data located in this study. In fact, the current calculations are quite different, both in terms of the models and the values or distributions of values selected for the parameters. In general, the calculation of ^{222}Rn release rates, Q_{total}, is broken into calculations of the releases through air exchange, Q_{exch}, and through diffusion, Q_{diff}. The diffusion release calculation is relatively straightforward, and we have used methods used in the previous assessment by Borak (1985), although we have used different parameter values. We note here that, as in the previous assessments (IT 1989), the results indicate releases through the diffusion pathway are relatively insignificant compared to releases through air exchange (see page J-29). The diffusion release calculations are retained for completeness. The calculation of air exchange releases is more complicated, and here we have deviated, in the details, from the previous methods used by Grumski (1987). The next subsection (see page J-11) of this appendix presents a more detailed description and justification of the basic models used in these current calculations.

For both time periods considered in this current assessment, one could try to estimate releases to a yearly or monthly time resolution. However, essentially all of the parameters used are assumed not to vary significantly from month to month or even from year to year (within the given assessment period). Thus, we feel that any additional resolution gained by

estimating releases for shorter time periods would be lost in the uncertainties of the estimates. So, for these current calculations, we will only estimate a release rate for each time period ("pre" and "post") that is assumed to apply to the entire time period. For convenience, the release rate estimates will be reported in activity released per year.

The current estimates of releases also account for parameter uncertainties in ^{222}Rn releases from the K-65 Silos, by performing the calculations using a Monte Carlo parameter uncertainty analysis. The Monte Carlo analysis uses distributions of potential values to represent the input parameters. Each distribution is based on the available (often limited) information about the parameter. Then, many iterations of the calculations are performed, each of which samples from the parameter distributions to obtain parameter values. For these current estimates, 1000 iterations of the calculations were performed. Thus, the result of the analysis is a distribution of potential values of the release quantities, which can be interpreted with specified percentile ranges (e.g., 5th to 95th percentile).

Calculational Strategy for Air Exchange Emissions

We first mention some assumptions made for the air exchange calculations. We assume that the ^{222}Rn concentration in outside air is negligible compared to the silo concentration so that outside air does not provide a source of Rn to the silo air. Since the releases of Rn through diffusion are shown, as in the previous assessments, to be relatively insignificant compared to air exchange releases (see page J-29), we assume the rate of removal of ^{222}Rn from the silo air space due to diffusion releases is negligible, compared to removal by ventilation. With these assumptions, the basic equation describing the rate of change in the silo air Rn concentration can be written (NCRP 1989):

$$\frac{dC_a}{dt} = \frac{P_{Rn}}{V_0} - C_a \lambda_{eff} \qquad \text{(J - 7)}$$

where

C_a = concentration of ^{222}Rn in the silo air,

P_{Rn} = the constrained (by the presence of the silo) rate of release of ^{222}Rn into the silo air (production term) from the K-65 source material (activity per time),

V_0 = volume of the air space in the silo above the K-65 material,

λ_{eff} = the effective removal rate of $^{222}Rn = \lambda_{Rn} + \lambda_v$,

λ_{Rn} = the decay constant for $^{222}Rn = 0.18129\ d^{-1}$, and

λ_v = ventilation rate of the silo, or fraction of the silo air exchanged with the outside per unit time (per day).

The diurnal cycling of the silo ventilation rate (especially during the post-sealing time period), and thus to a lesser extent the ^{222}Rn concentration are recognized. However, over a longer period of time the variations in these parameters are expected to be insignificant. Thus, we assume that equilibrium conditions exist, and that the ventilation rate, ^{222}Rn concentration, and ^{222}Rn production rate are constant over the periods of concern. Thus, we obtain the relationship:

$$P_{Rn} = C_a \lambda_{eff} V_0 \qquad \text{(J - 8)}$$

Because the silo air space is a single compartment volume, we assume the contained air to be well mixed. Thus, the air exchange release rate is simply the activity in the silo air space times the silo ventilation rate:

$$Q_{exch} = C_a \lambda_v V_0 \qquad \text{(J - 9)}$$

where Q_{exch} is the rate of release of ^{222}Rn from the silo through air exchange.

This can be rewritten:

$$Q_{exch} = C_a \lambda_{eff} V_0 (\lambda_v / \lambda_{eff}), \quad \text{or}$$

$$Q_{exch} = P_{Rn} (\lambda_v / \lambda_{eff}) \qquad \text{(J - 10)}$$

By expanding equation J-8, using $\lambda_{eff} = \lambda_v + \lambda_{Rn}$, and substituting for the product, $C_a \lambda_v V_0$, using equation J-9, we can also obtain:

$$Q_{exch} = P_{Rn} - C_a \lambda_{Rn} V_0 \qquad \text{(J - 11)}$$

Equations J-9, J-10, and J-11 provide alternative methods of calculating the air exchange release rate, depending on what information may be available. We note that equation J-9 is essentially the equation used in the previous assessment (Grumski 1987).

Strategy for Calculation of $Q_{exch,post}$ (1980–1987). For the period 1980–1987, measured concentrations of ^{222}Rn in the silo air (C_a) are available, from a set of samples taken by the FMPC in 1987. In fact, these are the only useable measurements of ^{222}Rn concentrations in the silos that we have located. We would like to use this information, and thus should select either equation J-9 or equation J-11 to calculate $Q_{exch,post}$. In addition, data are available on the silo temperature cycling (as discussed earlier, on page J-8) that can be used to calculate λ_v. There are two related problems with the use of equation J-11 for this situation. First, since the major penetrations in the silos have been sealed, we expect the ventilation rate to be very low. In particular, we expect λ_v to be significantly less than λ_{Rn}. If this is the case, then we expect the two terms in equation J-11, P_{Rn} and $(C_a \lambda_{Rn} V_0)$, to be approximately equal. For the uncertainty analysis then, we expect the uncertainty in the result, the difference of these two terms, to be large on a relative scale (relative standard deviation).

Second, as shown in a previous section of this appendix (see page J-4), the characterization of the K-65 waste material is not as complete as we would like. It appears from the recent sampling of the Silos that the material is fairly heterogeneous. The concentrations of ^{226}Ra in the important upper layers of the K-65 material are not well known; no measurements of the emanation fraction have been made, thus one might assume a potential range of 0.1 to 0.6 (Rogers et al. 1984); the diffusion coefficient has not been measured either, and the moisture contents of the important upper layers of the K-65 material are also not well characterized, so that diffusion coefficients spanning about two orders of magnitude are conceivable (Rogers et al. 1984). With all these uncertainties, the uncertainty in the calculation of P_{Rn} will be very large.

For these two reasons, the use of equation J-9, with the calculation of λ_v from the silo temperature cycling data, seems to be a better method, with less overall uncertainty.

Strategy for Calculation of $Q_{exch,pre}$ (1959–1979). For the period 1959–1979, no direct information is available about the Rn concentration, C_a, or about the silo ventilation

rate, λ_v. The Rn production rate, P_{Rn}, can be assumed the same as for the period 1980–1987, and obtained from the concentration and ventilation rate for the 1980–1987 period, or could be obtained by other methods. Indirect information about the Rn concentration is available in the exposure rate measurements on the silo domes. The short-lived daughters of ^{222}Rn, which will be present in a significant fraction of their equilibrium concentrations, emit gamma radiation. Thus Rn concentrations can be correlated to gamma exposure rates measured near the source of the Rn. We acknowledge that this is a rather uncertain way of estimating the Rn concentration, but it is the only approach we know of that uses the available data. Thus we will use the form of equation J-11 for calculating $Q_{exch,pre}$.

Air Exchange Releases for 1980 to 1987

As discussed above, the air exchange releases for this period after the sealing of the silo penetrations can best be calculated by:

$$Q_{exch,post} = C_{a,post}\lambda_{v,post}V_0 \quad \text{(J - 12)}$$

During the period from 1980 through 1987, the major penetrations through the silo domes, like the six-inch gooseneck pipe, had already been sealed. However, exchange of air between the silos and the atmosphere continued, through the numerous cracks in the concrete of the domes. Radon releases for this time period are based on measured concentrations of ^{222}Rn in silo air and on a silo ventilation rate calculated from the daily temperature change of silo air.

In this and following sections, we use the subscript "post" to refer to that parameter for the time period 1980 to 1987.

Radon concentration in silos 1980–1987. The silo interior air was sampled on November 4, 1987, prior to the operation of the Radon Treatment System (RTS) and prior to the application of the exterior foam layer to the silo domes (Grumski and Shanks 1988). The RTS is a system that pumps air from the silos through a series of calcium sulfate and charcoal beds, which adsorb ^{222}Rn from the circulating air (Grumski and Shanks 1988). This removes ^{222}Rn, and thus potential daughter products of ^{222}Rn, from the air space of the silos, and reduces the direct radiation exposure rates on the silo domes. The system is used to reduce radiation exposures to personnel involved in work on the silos.

The November 4, 1987, ^{222}Rn samples were analyzed by the FMPC and by Mound Laboratories, also in Ohio. The results are given in Table J-5.

The significant difference between the sampling bag and glass flask results for Silo 2 was noted in the report (Grumski and Shanks 1988). This report indicated that the difference was "...most likely the result of dilution error associated with the sample bag procedure." Because of this potential error in the results for the samples taken in sampling bags, the two results for sampling bag samples will be ignored for the rest of this analysis.

Thus, the sample estimate of the average concentration of ^{222}Rn in the silos for this measurement episode is 2.62×10^7 pCi L^{-1} and the standard deviation of the four measurements is 4.1×10^6 pCi L^{-1}, or about 16%. Since the measurements are radioactivity measurements, which are often assumed to follow normal distributions, the results are assumed to follow a normal distribution.

There is also uncertainty in the value of $C_{a,post}$ due to the presumed daily variations in the silo ventilation rate, $\lambda_{v,post}$. The silo ventilation rate is later estimated to be roughly 0.05 d^{-1}, or about 5% d^{-1}. In addition, only one sampling episode was performed during the period 1980 to 1987.

Table J-5. Results of K-65 Silo Gas Sample Analyses, Samples Taken November 4, 1987

Silo, sample container	WMCO Analysis (pCi L^{-1})	Mound Analysis (pCi L^{-1})
Silo 1, sampling bag	—	2.3×10^7
Silo 2, sampling bag	—	1.3×10^7
Silo 1, glass flask	2.1×10^7 [a]	2.5×10^7 [b]
Silo 2, glass flask	3.0×10^7	2.9×10^7 [b]

[a] The results for this sample given in the report (Grumski and Shanks 1988), appeared to contain a calculational error. The value presented here is the average of the eight measurements, after the apparent error was corrected (by the authors of this current report).

[b] This value appears to be the average of concentrations measured for two sample flasks.

Typically, the standard deviation of an average value is the standard deviation of the measured values divided by the square root of the number of samples. However, because of the additional, unquantified uncertainties, we instead assume that the standard deviation of the average concentration is equal to the standard deviation for the four measured values. Thus, the distribution of values of $C_{a,post}$ is considered to be a normal distribution with mean 2.62×10^7 pCi L^{-1} and standard deviation 4.1×10^6 pCi L^{-1}.

Silo air volume 1980–1987. The volume of air space in the silos, V_0, can be calculated as the sum of the volume of air in the dome part of the silo, V_{dome}, and the volume of air in the cylindrical part of the silo above the K-65 residue material, V_{cyl}. We assume the dome surface is spherically shaped, so these volumes are calculated as:

$$V_{dome} = \frac{\pi h^2}{3}(3R - h) \qquad \text{(J - 13)}$$

where

h = the height of the dome (above the silo walls),
R = $(r^2 + h^2)/2h$, the radius of the "sphere" of which the dome surface is a part, and
r = the radius of the silo. And,

$$V_{cyl} = \pi r^2 H \qquad \text{(J - 14)}$$

where H is the distance from the K-65 residue material to the top of the silo walls, which is the thickness of the cylindrical air layer.

Two drawings by the original designers and builders of the K-65 silos indicate the size of the silos to be 80 ft inside diameter, with a wall height of 26 ft 8 in, and inside dome height

of an additional 9 ft 4 in (Preload 1951a and Preload 1951b). The unloading manhole, which is located very close to the center of the dome, is shown as 36 ft above the silo floor. The four influent manholes are shown to be located equally spaced on a circle of 25 ft radius from the center of the dome, and about 32 ft above the silo floor.

From these data, V_{dome} can be directly calculated. First, with h = 9.33 ft and r = 40 ft, R is determined to be 90.4 ft. Then, V_{dome} is calculated to be 23,900 ft^3.

A small number of documents have been found which can be used to estimate the value of H to calculate V_{cyl}. From a drilling and sampling episode in 1972, the depths of K-65 material were determined to be 20 ft in Silo 1 and 22 ft in Silo 2 (Nelson 1972b). Thus, for Silo 1, H = 26.67 ft − 20 ft = 6.67 ft. And, for Silo 2, H = 26.67 ft − 22 ft = 4.67 ft. With these values of H, V_{cyl} is estimated to be 33,500 ft^3 for Silo 1 and 23,500 ft^3 for Silo 2. The total volume is then estimated to be 57,000 ft^3 for Silo 1 and 47,000 ft^3 for Silo 2.

In 1978, gamma exposure rates were measured in Silo 1, at varying distances above the K-65 residue (Boback 1978). The farthest measurement location was 13 ft above the residue surface, and was also noted to be at the bottom of a manhole opening. It was not noted whether the manhole was one of the influent manholes or the unloading manhole. If the location was one of the influent manholes, the thickness of the K-65 material can be estimated to be 32 ft − 13 ft = 19 ft. Thus, H = 26.67 ft − 19 ft = 7.67 ft, V_{cyl} = 38,500 ft^3 and V_0 = 62,000 ft^3. If the location was the unloading manhole, the K-65 material thickness can be estimated to be 36 ft − 13 ft = 23 ft. Thus, H = 26.67 ft − 23 ft = 3.67 ft, V_{cyl} = 18,400 ft^3, and V_0 = 42,000 ft^3.

In 1958, Silo 2 was decanted and removed from service, with a stated content of 883,400 gallons of residue (Noyes 1958). Since the residue was pumped into the silos as a slurry, we assume the residue occupied a cylindrical shape. Thus, the thickness of residue can be estimated to be 23.5 ft. Thus, H = 26.67 ft − 23.5 ft = 3.17 ft, V_{cyl} = 15,900 ft^3, and V_0 = 40,000 ft^3.

The air volumes of the silos have also been determined by WMCO to be 55,815 ft^3 for Silo 1 and 45,762 ft^3 for Silo 2 (Shanks 1988). These volumes were based on depths of the residue of 20 ft in Silo 1 and 22 ft in Silo 2. These residue depths are the same as those of Nelson (1972b), but were not referenced in the WMCO calculations.

As part of the FMPC Remedial Investigation, the silos were sampled by WMCO in 1989 (DOE 1990). During this sampling episode, the average penetration into the K-65 residue material was 20 ft. No individual values of the penetration were given in the report. The value of 20 ft results in an estimate of V_0 of 57,000 ft^3, as noted earlier.

The range of these estimates of V_0 is from 40,000 ft^3 to 62,000 ft^3. Since we have no information that more definitively determines V_0, we assume the distribution of potential values of V_0 to be uniform, with minimum 40,000 ft^3 and maximum 62,000 ft^3.

Silo ventilation rate 1980–1987. As noted earlier, monitoring of the temperature and pressure differential of the K-65 Silos was performed in 1987 by WMCO (Grumski 1987). It was concluded that the silos cannot hold any significant pressure and thus that increases in the temperature of the internal silo air resulted in the volumetric expansion of the air and the release of "excess" volume to the atmosphere (Grumski 1987). Since the silos can not hold any significant pressure, it is certainly plausible that the cracks and other remaining

penetrations in the silo domes are large enough and numerous enough that additional ventilation of the silos occurs, due to winds across the silo domes. For the present work, it is assumed that the silo ventilation rate is the sum of a ventilation rate due to the temperature effects and a ventilation rate due to wind effects. That is,

$$\lambda_{v,post} = \lambda_{v,\Delta T} + \lambda_{v,wind} \qquad \text{(J - 15)}$$

We note that the previous assessments did not specifically calculate a silo ventilation rate, although the ventilation rate was implicit in their ^{222}Rn release calculations (Grumski 1987; IT 1989).

Temperature effects. The ventilation rate due to the daily temperature changes, $\lambda_{v,\Delta T}$, is the fraction of the silo air exhaled due to the temperature changes per some unit time period, with units of (air changes) per time. Thus:

$$\lambda_{v,\Delta T} = \Delta V / V_0 \qquad \text{(J - 16)}$$

As discussed earlier in the evaluation of previous estimates (see equation J-5), the ideal gas law gives:

$$\Delta V = (\Delta T / T_0) V_0 \qquad \text{(J - 17)}$$

thus

$$\lambda_{v,\Delta T} = \Delta T / T_0 \qquad \text{(J - 18)}$$

where we define

ΔV = the increase in volume per day,
ΔT = the increase (only) in temperature per day (K d^{-1}),
V_0 = the initial silo air volume above the K-65 material, and
T_0 = the initial temperature of the silo air (K).

As noted earlier in the discussion of previous estimates (see page J-8), usable temperature and pressure monitoring data for the two K-65 silos were obtained for 11 complete days (and a few shorter periods also) (Grumski 1987; Shanks 1991). From this data, which was collected every two hours, the silo daily temperature increase and the initial temperature of the silo air can be determined. However, since only 11 days of data were obtained, the direct use of this data to estimate the annual average value of $\Delta T/T_0$ for the silos could introduce a significant bias. Instead, the daily silo values of $\Delta T/T_0$ can be correlated to daily temperature changes at the Cincinnati airport. Then, the correlations can be used to estimate the average value of $\Delta T/T_0$ for the silos from the Cincinnati temperature data.

Since we are interested only in the increase in silo temperature each day, ideally we would correlate the daily silo values of $\Delta T/T_0$ with the increase (only) in temperature at the Cincinnati airport. However, it is impractical to determine the airport temperature increase for each day of a full year, as would be required. Instead, we determine the difference between the maximum and minimum airport temperature for each day, and then correlate the daily silo values of $\Delta T/T_0$ to this difference. It is recognized that there are uncertainties introduced by performing the correlation in this manner. For example, on many days, the temperature falls during the day so the silo temperature increase, and $\Delta T/T_0$, is zero, but

the airport temperature difference (maximum temperature – minimum temperature) is still positive.

The data obtained to perform the correlation are given in Tables J-6 and J-7. The silo temperature increase and minimum temperature data were obtained from the previous temperature and pressure monitoring of the silos (Shanks 1991). For each silo, the monitoring results included a "bottom" temperature, near the bottom of the air space in the silo, and a "top" temperature, near the top of the silo air space. The average value of $\Delta T/T_0$, given in Table J-6, has been calculated as follows. First, for each silo, the top and bottom temperatures at each measurement time were averaged, as a best estimate of the temperature in the silo air for that point in time. Next, the increase in temperature and the initial temperature were determined for each silo for each of the 11 days, and were converted to the (absolute) Kelvin scale (K). Then, the values of $\Delta T/T_0$ for each silo for each day were calculated. Finally, the average value of $\Delta T/T_0$, for each day, was calculated as the average of the values for the two silos for that day.

Table J-6. K-65 Silo Values of $\Delta T/T_0$ — Data Used for a Linear Correlation [a]

	Silo 1 data[b]			Silo 2 data[b]			Average
Date	T_0 (°F)	ΔT (°F d^{-1})	$\Delta T/T_0$ (d^{-1})	T_0 (°F)	ΔT (°F d^{-1})	$\Delta T/T_0$ (d^{-1})	$\Delta T/T_0$ (d^{-1})
3/27/87	50.65	20.15	0.0395	52.35	22.85	0.0447	0.0421
3/29/87	53.6	21.6	0.0421	56.25	23.65	0.0459	0.0440
3/30/87	42.85	0	0	41.9	0	0	0
3/31/87	40.8	4.6	0.0092	39.1	5.15	0.0103	0.0098
4/01/87	38.85	14.2	0.0285	36.6	16.2	0.0327	0.0306
4/02/87	43.95	12.	0.0238	43.3	14.1	0.0280	0.0259
4/03/87	38.5	11.3	0.0227	37.55	12.6	0.0254	0.0240
4/04/87	40.25	3.15	0.0063	39.	3.6	0.0072	0.0068
5/09/87	61.95	30.9	0.0593	63.1	35.1	0.0672	0.0632
5/10/87	65.25	30.1	0.0574	67.5	34.1	0.0647	0.0610
5/11/87	68.35	27.1	0.0514	71.25	28.8	0.0543	0.0528

[a] The values of ΔT and T_0 must be expressed in absolute temperature units (K) before the ratio is computed.

[b] T_0 and ΔT data obtained from Shanks (1991).

Records of the hourly temperature at the Cincinnati airport have been obtained for the period 1948 to 1987, by year (NOAA 1987). The maximum temperature, T_{max}, and the minimum temperature, T_{min}, were extracted for each of the 11 days on which the silo temperature was measured, and are shown in Table J-7. The difference $T_{max} - T_{min}$, in Table J-7, has been calculated for this analysis.

We note that some relationship is expected between the minimum temperature and the daily temperature change at the Cincinnati airport. A linear regression of the values of ($T_{max} - T_{min}$) versus the values of T_{min} for 1987 was performed. The regression coefficient

was determined to be R = 0.075. With this small value of the regression coefficient, we assume the relationship between ($T_{max} - T_{min}$) and T_{min} is weak enough to be considered insignificant for our analysis. Thus, we neglect this possible relationship.

Table J-7. Temperature Difference at Cincinnati Airport — Data Used for a Linear Correlation[a]

Date	Maximum T_{max} (°F)	Minimum T_{min} (°F)	$T_{max} - T_{min}$ (°F)
3/27/87	65	44	21
3/29/87	77	44	33
3/30/87	48	29	19
3/31/87	33	24	9
4/01/87	47	24	23
4/02/87	43	31	12
4/03/87	37	27	10
4/04/87	41	28	13
5/09/87	80	43	37
5/10/87	85	53	32
5/11/87	84	60	24

[a] T_{min} and T_{max} data obtained from NOAA (1987).

A linear correlation of the average values of $\Delta T/T_0$ (dependent variable) to the Cincinnati airport temperature difference (independent variable), $T_{max} - T_{min}$, was performed using a least squares regression. The regression coefficient is R = 0.80. The regression line is given by:

$$\Delta T/T_0\ (\mathrm{d}^{-1}) = (0.00179\ ^\circ\mathrm{F}^{-1}\ \mathrm{d}^{-1}) \times (T_{max} - T_{min}\ (^\circ\mathrm{F})) - 0.00516\ \mathrm{d}^{-1} \qquad \text{(J - 19)}$$

For this regression line, the standard error of estimate, $S_{Y|X}$, is 0.0138 d^{-1}.

From the hourly records of temperature at the airport, additional data were obtained for the complete year 1987 (NOAA 1987). The average of the daily maximum temperatures was determined to be 65.08 °F. The average of the daily minima was determined to be 45.62 °F. The average daily difference (average of ($T_{max} - T_{min}$)) is equal to the difference of the averages of the maxima and minima. Thus, the average daily difference for 1987 is 65.08 – 45.62 = 19.46 °F. This value is also assumed to represent the average daily difference for the assessment period 1980 to 1987.

Thus, the annual average value of $\Delta T/T_0$, and thus $\lambda_{v,\Delta T}$ for the period 1980 to 1987 is estimated from the regression line and the average daily difference as:

$$\begin{aligned}\lambda_{v,\Delta T} &= \Delta T/T_0 \\ &= (0.00179\ ^\circ\mathrm{F}^{-1}\ \mathrm{d}^{-1}) \times (19.46\ ^\circ\mathrm{F}) - 0.00516\ \mathrm{d}^{-1} \\ &= 0.0297\ \mathrm{d}^{-1} \qquad \text{(J - 20)}\end{aligned}$$

It is assumed that the conditional distribution of $\Delta T/T_0$, at the given value of $T_{max} - T_{min}$ = 19.46 °F, is a normal distribution with standard deviation $S_{Y|X}$. Thus, we consider the distribution of potential values of $\Delta T/T_0$ to be a normal distribution with mean 0.0297 d^{-1} and standard deviation 0.0138 d^{-1}. However, with this mean and standard deviation, there is a significant chance that negative values of $\Delta T/T_0$ might be selected from the distribution. Since such negative values are meaningless for the calculation of the ventilation rate, we truncate the distribution at 0, disallowing negative values.

Wind effects. As discussed earlier, it is plausible that the cracks in the silo domes are numerous enough and large enough that the action of winds on the domes could create additional ventilation in the silos, represented by $\lambda_{v,wind}$. However, no data have been found to substantiate an estimate of $\lambda_{v,wind}$. Thus, we arbitrarily assume that $\lambda_{v,wind}$ ranges from zero to the value of $\lambda_{v,\Delta T}$. We assume that $\lambda_{v,wind}$ follows a uniform distribution with minimum 0 and maximum $\lambda_{v,\Delta T}$ (d^{-1}).

Silo Radon Production Rate

From the concentration of ^{222}Rn measured after the sealing of the silo openings, the rate of release of ^{222}Rn into the silo air (production term) from the K-65 material can be estimated. This result will be used later for calculating the silo ventilation rate for the period 1959 to 1979. From an assumption of an equilibrium ^{222}Rn concentration in the silo air, the rate of release of ^{222}Rn into the silo air is equal to the loss of ^{222}Rn from the silo air by decay and by release to the atmosphere. As given in equation J-8, this is represented as (see also Collé 1981):

$$P_{Rn} = C_{a,post} V_0 \lambda_{eff,post} \qquad \text{(J - 21)}$$

where

P_{Rn} = the constrained (by the presence of the silo) rate of release of ^{222}Rn into the silo air (production term) from the source material (pCi d^{-1}),

$C_{a,post}$ = the concentration of ^{222}Rn in the silo air (pCi L^{-1}); - measured

V_0 = volume of the silo air space, as used earlier, and - known

$\lambda_{eff,post}$ = the effective removal rate of ^{222}Rn, the sum of the ^{222}Rn decay constant, λ_{Rn}, and the ventilation rate, $\lambda_{v,post}$ (d^{-1} or other). $\lambda_{eff} = \lambda_{Rn} + \lambda_v$ known calculated using diff pa

The ^{222}Rn concentration, $C_{a,post}$; silo air volume, V_0; and silo ventilation rate, $\lambda_{v,post}$, were discussed previously in this appendix.

The half life of ^{222}Rn is 3.8235 d (Walker, et al. 1983). Thus, the decay constant for ^{222}Rn is 0.18129 d^{-1}. For purposes of our calculations, this value is assumed to have negligible uncertainty.

Air Exchange Releases for 1959 to 1979

In 1958 the second silo was decanted, with the excess water removed through the weirs in the sides of the silo. Thus, during the period 1959 to 1979 the K-65 material in the silos should not have been covered with standing water. The six-inch gooseneck pipe vent was open from the silos to the atmosphere. For this time period, the free air exchange releases

are estimated using equation J-11 with the ^{222}Rn concentration based on exposure rate measurements on the domes of the silos. That is,

$$Q_{exch,pre} = P_{Rn} - C_{a,pre}\lambda_{Rn}V_0 \qquad \text{(J - 22)}$$

The calculations of V_0 and λ_{Rn} were previously discussed. It is assumed that the constrained rate of release of ^{222}Rn into the silo air from the K-65 material, P_{Rn}, has not changed significantly from 1959 through 1987. It is recognized that the release of Rn into the silos would be higher for a lower silo Rn concentration (e.g. the change from the 1980–1987 period back to the 1959–1979 period), since the diffusion of Rn out of the K-65 material is a concentration constrained process. For this assessment, we make the first order approximation that this effect is negligible. The other major parameter that might have changed during this time, that would affect this production term, is the moisture content of the uppermost part of the K-65 material in the silos. However, no applicable information has been located that could be used to determine the time history of this moisture content. We have assumed that it has not changed enough to significantly alter the rate of release of ^{222}Rn into the silo air from the K-65 material. Thus, the production rate, as calculated earlier (see page J-19) for the 1980–1987 period is used for this period also.

Here, and in the following sections, the subscript "pre" refers to that parameter for the time period 1959 to 1979.

Radon Concentration In Silos 1959–1979. To this point, no useful measurements of the ^{222}Rn concentration in the silos for the period 1959 to 1979 have been located. However, an alternative is to make use of the fact that two of the short-lived daughters of ^{222}Rn, ^{214}Pb and ^{214}Bi, emit gamma radiation in significant quantities. Because these daughters would be present with ^{222}Rn in an appreciable fraction of equilibrium, the high concentrations of ^{222}Rn in the silo air will have an associated, significant gamma exposure rate.

If measurements of the exposure rate are obtained for a consistent geometry, for a time period when the ^{222}Rn concentration is also known, an exposure rate factor (mR h^{-1} per pCi L^{-1} ^{222}Rn, or similar) can be developed. Then, the ^{222}Rn concentration can be estimated for other time periods when only exposure rate data exist. This is the approach taken. The exposure rate factor (ERF) will be developed based on ^{222}Rn concentration and exposure rate data for the period around 1987. Then, the ^{222}Rn concentration will be estimated for the period 1959 to 1979. That is:

$$\text{ERF} = \frac{X_{post} - X_{bkg}}{C_{a,post}} \qquad \text{(J - 23)}$$

where

ERF = exposure rate factor (mR h^{-1} per pCi L^{-1}),

X_{post} = the gross exposure rate on the silo domes during the period 1980–1987 (mR h^{-1}), and

X_{bkg} = the "background" exposure rate on the silo domes (mR h^{-1}). This exposure rate would include contributions from sources other than the ^{222}Rn daughters in the silo air space. Since this would include contributions from ^{222}Rn daughters in the K-65 residues, this background exposure rate will be much greater than a typical environmental background exposure rate.

Then

$$C_{a,pre} = \frac{X_{pre} - X_{bkg}}{ERF} \qquad (J-24)$$

where

$C_{a,pre}$ = concentration of ^{222}Rn in the silo air (pCi L^{-1}), and

X_{pre} = the gross exposure rate on the silo domes during the period 1959–1979 (mR h^{-1}).

These two equations can be simplified to:

$$C_{a,pre} = C_{a,post}\left(\frac{X_{pre} - X_{bkg}}{X_{post} - X_{bkg}}\right) \qquad (J-25)$$

Some results of radiation exposure measurements on the domes of the K-65 silos have been located and are summarized in Table J-8.

The "contact" measurement data will be used in this analysis because the only measurements made after ^{222}Rn had been removed from the silos were made on contact. The measurements made at 4 ft above the surface and the measurements for which the height was not specified will not be included in this analysis. Two other measurements will also be disregarded. First, the low value of those made on contact with Silo 2 (85 mR h^{-1}) in November 1980 was made on the edge of the silo dome, and was thus not considered comparable to the other measurements. Second, the extremely high result of April 1986 was obtained at a crack in the dome surface (Fleming 1986), through which ^{222}Rn was probably moving, and in which decay products had probably plated out. Thus, this measurement is also not considered indicative of the silo ^{222}Rn concentration in the same manner as the other measurements.

The data for the period prior to sealing the openings do not indicate a significant variation in exposure rate from 1964 through 1973. These measurements ranged from 65 to 90 mR h^{-1}. Little information exists about the number and location of measurements made for each measurement episode. Some results were averages, while others were ranges.

The data for the period after sealing the openings also do not indicate a significant variation in exposure rate from 1980 to 1987, especially with the uncertainty of instruments used and their response characteristics. These measurements ranged from 168 to 250 mR h^{-1} (the measurements after operation of the Radon Treatment System (RTS) are not included).

The data taken after operation of the RTS, in November 1987, can be used to estimate the "background" exposure rate due to sources other than the ^{222}Rn in the silo air. As discussed earlier, the RTS is a system to remove Rn and potential daughter products from the silo air space (see page J-13).

Table J-8. Measurements of Exposure Rate on Domes of K-65 Silos Construction through 1987

Date of Measurement	Silo	Height of Measurement	Exposure rate (mR h^{-1})	Comments (reference)
		Prior to Sealing Silo Openings		
Apr 1964	1	contact	75	Average value, probably silo 1 (Starkey 1964).
Mar 1972	ns[a]	ns	30	(Levy 1972)
Mar 1972	ns	contact	75	Maximum reading, assumed to be on contact (Nelson 1972a).
May 1973	1	contact	65–90	Assumed on contact since other locations were (Boback 1973).
May 1973	2	contact	70–75	(Boback 1973)
Jul 1973	2	ns	35	Near center of dome (Levy 1973).
ns	ns	contact	90	Specified as before sealing of openings in 1979 (Boback 1980).
		After Sealing Silo Openings		
Apr 1980	1	contact	250	(Green 1980a)
	1	4 ft	150	(Green 1980a)
	2	contact	200–250	(Green 1980a)
	2	4 ft	150	(Green 1980a)
ns	ns	contact	250	Specified as after sealing of openings in 1979 (Boback 1980).
Nov 1980	1	contact	175	(Green 1980b)
Nov 1980	1	4 ft	140	(Green 1980b)
Nov 1980	2	contact	85–175	The low value was near edge, rather than center (Green 1980b).
Nov 1980	2	4 ft	45–100	The low value was near edge, rather than center (Green 1980b).
Apr 1986	2	contact	850	Measured at crack in dome; other results not legible (Fleming 1986).
Nov 1987	1	contact	168–208	Baseline, average 193 (Grumski and Shanks 1988).
Nov 1987	1	contact	35.5–68	After operation of RTS[b], average 55 (Grumski and Shanks 1988).
Nov 1987	2	contact	221–250	Baseline, average 232 (Grumski and Shanks 1988).
Nov 1987	2	contact	60–76	After RTS, average 68 (Grumski and Shanks 1988).

[a] "ns" indicates that the parameter was not specified in the reference document.

[b] RTS is the acronym for the Radon Treatment System.

The RTS was operated in November 1987, prior to the installation of a foam layer on the silo domes (Grumski and Shanks 1988). The system operated on one silo at a time, with a flow rate of about 1000 ft^3 min^{-1}, and was operated until radiation levels on the dome surface stopped decreasing (Grumski and Shanks 1988). With this flow rate and an average nominal silo volume of 51,000 ft^3, the ventilation rate was (1000 ft^3 min^{-1})/(51000 ft^3) = 0.020 min^{-1}, or 1.2 h^{-1}. The exposure rate measurements were taken during operation of the RTS, but after it had been operating 4.6 h for Silo 1 and after 3.5 h for Silo 2 (Grumski and Shanks 1988). With these flow rate and operating times, and an assumed removal efficiency close to 100%, the ^{222}Rn concentrations in the silo air space should have been reduced to less than 3% of the initial concentrations. Also, in this operating time, any ^{222}Rn daughter radioactivity deposited on surfaces in the silos would have decayed to less than 2% of its original activity.

Thus, for this analysis, the exposure rate measurements made after operation of the RTS are considered to represent the "background" exposure rate, in the absence of ^{222}Rn daughters in the silo air. This background is primarily due to radiation from the radioactivity contained in the K-65 material in the silos (including trapped ^{222}Rn daughters). This set of measurements consists of four measurements, regularly spaced, on each silo dome. The range of the eight measurements was from 35.5 to 76 mR h^{-1} (Grumski and Shanks 1988).

For all of these exposure rate measurements, there is uncertainty in the results due to lack of knowledge about what instruments were used, and how the instruments were calibrated. It is noted that most survey instruments do not have a flat curve of response versus radiation energy, and so tend to have biases at varying energies. In addition, the measurements of the gross exposure rate before and after the vent sealing have uncertainties due to lack of knowledge about the exact measurement locations. These uncertainties combine to produce uncertainty about the comparability of the measurements made at different times. Because of this, we assume that the potential values of X_{pre}, X_{post}, and X_{bkg} are all represented by uniform distributions, with ranges twice the observed ranges.

Thus, X_{bkg} is considered to be represented by a uniform distribution with minimum 15.25 mR h^{-1} and maximum 96.25 mR h^{-1}.

The range to be used for X_{pre} overlaps the range of X_{bkg}, which could result in calculated values of $C_{a,pre}$ that are less than zero. To correct this, the distribution used for X_{pre} is a uniform distribution with a minimum that is the greater of 52.5 mR h^{-1} and X_{bkg}. This ensures that X_{pre} is always at least as great as X_{bkg}. The maximum value of the distribution is 102.5 mR h^{-1}.

And, X_{post} is considered to be represented by a uniform distribution with minimum 127 mR h^{-1} and maximum 291 mR h^{-1}.

Diffusion Releases

The diffusion releases for the period 1980 to 1987 are calculated using the same methods used in the previous assessment (IT 1989; Borak 1987). However, since the concentration of

^{222}Rn in the silos has been measured, the calculated releases are based on the measured ^{222}Rn concentration, rather than on a concentration calculated from characteristics of the K-65 waste material. As was described earlier, the flux of ^{222}Rn diffusion through the concrete dome of the silos can be calculated by (Borak 1985; Collé 1981):

$$J = \frac{E_c \lambda_{Rn} l_c C_a}{\sinh\left(\frac{L}{l_c}\right)} \qquad \text{(J - 26)}$$

where

J = ^{222}Rn flux from the silo dome surfaces to the surrounding air (pCi m^{-2} d^{-1}, or similar),

E_c = total porosity of the dome concrete,

λ_{Rn} = decay constant of ^{222}Rn (d^{-1}, or other as appropriate),

l_c = diffusion length of ^{222}Rn in the dome concrete (cm),

C_a = concentration of ^{222}Rn in the silo air (pCi L^{-1}), and

L = thickness of the dome concrete (cm).

The diffusion release rate is then calculated as:

$$Q_{diff} = JA, \qquad \text{(J - 27)}$$

where A is the surface area of the silo domes (ft^2, or other).

These equations are applied to the two different time periods by using $C_{a,post}$ to determine $Q_{diff,post}$ and $C_{a,pre}$ to determine $Q_{diff,pre}$. The other variables are not dependent on the time period.

Concrete Porosity. A National Bureau of Standards (NBS) review report cited a measured value of concrete porosity of 0.265 from one study and an assumed range of 0.05 to 0.25 from another study (Collé 1981). The porosity used in the previous assessment was 0.3 (Borak 1987), although the source of the value was not cited. Because of the very limited amount of data found, and the lack of data specific to the FMPC K-65 silos, we assume that the potential values of E_c follow a uniform distribution with range equal to the range cited by the NBS report. Thus, the minimum of the distribution is assumed to be 0.05, and the maximum 0.265.

Radon Diffusion Length in Concrete. The NBS review report cited measurements of the ^{222}Rn diffusion coefficient in concrete, that would equate to diffusion lengths from 7.43 cm to 12.7 cm (Collé 1981). Nazaroff and Nero (1988) cite values of the diffusion length in concrete from 6 cm to 20 cm. The diffusion length in concrete used in the previous assessment was 12 cm (Borak 1987). This value was justified by Borak based on a referenced range of values from 6 cm to 23 cm measured for intact concrete (Borak 1986; Jonassen and McLaughlin 1978 [cited by Borak 1986]; Krisiuk et al. 1971 [cited by Borak 1986]). Again, the data found are limited, and are not specific to the K-65 domes. Thus the range of literature values is used and we assume that the potential values of l_c are represented by a uniform distribution with minimum 6 cm and maximum 23 cm.

Silo Dome Thickness. A review of the K-65 silos' history indicated that the thickness of the domes was 4 in (Shanks and Vogel 1988). However, an FMPC report about proposed stabilization activities on the silos indicated that the domes were designed to be 8 in thick at

the silo wall, tapering to 4 in thick at the dome center (Grumski 1987). However, we have reviewed some of the original engineering drawings for the silo construction, and this latter characterization appears to be a misinterpretation. The silo design drawing indicates that the domes would be 8 in thick at the silo wall, but would taper to a thickness of 4 in within about 2 ft from the wall (Preload 1951a). Thus, the thickness of 8 in is only at the very edge of the domes, and is ignored for this analysis.

In addition, a structural assessment of the silo domes was performed in 1985. As part of this assessment, the thickness of the domes were measured, and were indicated to be as thin as 3 in for portions of the centers of the domes, where deterioration has occurred (Camargo 1986). As an estimate of the mean thickness of the domes is not available, we consider the potential values of L to be represented by a uniform distribution with minimum 3 in and maximum 4 in.

Dome Surface Area. The silo dome surfaces are assumed to be portions of a sphere. As such, their surface area, A, can be calculated as:

$$A = 2\pi R^2\left(1-\sqrt{1-\frac{r^2}{R^2}}\right) \qquad \text{(J - 28)}$$

where

R = $(r^2 + h^2)/2h$, the radius of the "sphere" of which the dome surface is a part,
h = the height of the dome (above the silo walls), and
r = the radius of the silo.

As discussed earlier, h = 9.33 ft and r = 40 ft, and so R is determined to be 90.4 ft. Thus, A = 5300 ft^2. For the purposes of these calculations, the uncertainty in A is assumed negligible.

Radon Decay Constant. As discussed earlier, the decay constant for ^{222}Rn is 0.18129 d^{-1} and is also assumed to have negligible uncertainty.

Radon Daughter Releases

For this preliminary source term estimate, a relatively crude estimate of the releases of the short-lived ^{222}Rn daughters, ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po will be developed. We simply assume that the releases of the daughters are equal to the air exchange ^{222}Rn releases times the equilibrium factor:

$$Q_{daught} = Q_{exch}F \qquad \text{(J - 29)}$$

where Q_{daught} is the release rate of each of the four short-lived daughters and F is the equilibrium factor.

No information about the fractional equilibrium of short-lived ^{222}Rn daughters in silo air has been found. The range of possible values of the equilibrium fraction is from 0 to 1. Much of the research into Rn daughters has been focused on homes and occupational environments. The range of equilibrium fractions measured in houses is at least from 0.1 to 0.9 (NCRP 1988). However, houses typically have ventilation rates between about 0.2 and 3 h^{-1} (Nazaroff and Nero 1988), which is much greater than the calculated ventilation rates of the silos ($\lambda_{v,post}$ nominally about 0.002 h^{-1} and $\lambda_{v,pre}$ nominally about 0.05 h^{-1}). It is known that the equilibrium fraction in an enclosed space decreases with increasing ventilation

(NCRP 1989). However, at very low ventilation rates, low concentrations of condensation nuclei may lead to significantly increased unattached fractions of Rn daughters, and thus to significantly increased deposition of daughters on surfaces and decreased equilibrium fraction (Nazaroff and Nero 1988).

In addition, daughters could deposit along the release pathway (in the cracks or gooseneck vent pipe), before reaching the atmosphere. No information has been located relevant to this aspect of the release. For this preliminary evaluation, we assume that such deposition does not occur.

At this point, the characteristics of the silo aerosols are not well enough understood to allow a useful model of the airborne concentrations of Rn daughters in the silos. Therefore, for this preliminary source term estimate, it is assumed that the potential values of F are uniformly distributed with a minimum of 0 and a maximum of 1.

Implementation of Calculations

The Monte Carlo calculations for this analysis were performed using a spreadsheet software package on an IBM-compatible microcomputer. One thousand iterations of the calculations were performed. The following sections describe some of the details of these calculations.

Generation of the Parameter Distributions. The spreadsheet package includes a built-in function that returns a random number uniformly distributed between 0 and 1 (not inclusive), $U(0,1)$. Uniformly distributed random variables with minimum a and maximum b, $U(a,b)$ were generated as follows. First, a value u from $U(0,1)$ is generated. Then we set $x = a + (b - a)u$. Then x is a sample from the uniform distribution $U(a,b)$.

Normally distributed random variables with mean μ and standard deviation σ, $N(\mu,\sigma)$, were developed as follows. First, a value u from $U(0,1)$ is generated. Then we set $x_1 = P^{-1}(u)$, where P^{-1} is the inverse to the standard normal cumulative distribution function. In this case, we have used a rational approximation to P^{-1}, obtained from Abramowitz and Stegun (1972). Then x_1 is a sample from the standard normal distribution. Then we set $x_2 = \mu + \sigma x_1$. Then x_2 is a sample from a normal distribution with mean μ and standard deviation σ.

Equations for 1980–1987 air exchange. As was discussed previously, the air exchange releases for the period 1980 to 1987 can be calculated by:

$$Q_{exch,post} = C_{a,post}\lambda_{v,post}V_0 \qquad \text{(J - 12)}$$

where

$$\lambda_{v,post} = \lambda_{v,\Delta T} + \lambda_{v,wind} \qquad \text{(J - 15)}$$

The distribution chosen for $\lambda_{v,wind}$ is a uniform distribution with minimum 0 and maximum equal to $\lambda_{v,\Delta T}$. Thus, for a single calculation:

$$\lambda_{v,post} = \lambda_{v,\Delta T} + u\lambda_{v,\Delta T} \qquad \text{(J - 30)}$$

where u is a random number selected from the uniform distribution with minimum 0 and maximum 1, $U(0,1)$. By factoring;

$$\lambda_{v,post} = \lambda_{v,\Delta T}(1 + u) \qquad \text{(J - 31)}$$

By substituting $k_{v,wind}$ = a random number from the uniform distribution with minimum 1 and maximum 2, this is rewritten:

$$\lambda_{v,post} = \lambda_{v,\Delta T} k_{v,wind} \qquad \text{(J - 32)}$$

At this point we substitute for $\lambda_{v,\Delta T}$ to obtain:

$$\lambda_{v,post} = (\Delta T/T_0) k_{v,wind} \qquad \text{(J - 33)}$$

This last (Eqn. J-33) is the equation used in the spreadsheet calculations, with no units conversion needed.

Then, the release rate is calculated in the spreadsheet as:

$$Q_{exch,post} = C_{a,post} \lambda_{v,post} V_0 CF_1 \qquad \text{(J - 34)}$$

where CF_1 is the units conversion factor. The units of the result, $Q_{exch,post}$, are Ci y^{-1}. The units used for the parameters are pCi L^{-1} for $C_{a,post}$; d^{-1} for $\lambda_{v,post}$; and ft^3 (per silo) for V_0. Thus,

$$CF_1 = (10^{-12}\ \text{Ci pCi}^{-1})(365.25\ \text{d y}^{-1})(28.317\ \text{L ft}^{-3})(2\ \text{silos})$$
$$= 2.0686\times10^{-8}\ \text{Ci d L pCi}^{-1}\ \text{y}^{-1}\ \text{ft}^{-3} \qquad \text{(J - 35)}$$

Equations for 1959–1979 air exchange. As was discussed previously, the air exchange releases for the period 1959 to 1979 can be calculated by:

$$Q_{exch,pre} = P_{Rn} - C_{a,pre} \lambda_{Rn} V_0 \qquad \text{(J - 22)}$$

It was noted earlier that the ^{222}Rn concentration can be calculated as:

$$C_{a,pre} = C_{a,post} \left(\frac{X_{pre} - X_{bkg}}{X_{post} - X_{bkg}} \right) \qquad \text{(J - 25)}$$

This equation is used in the spreadsheet to obtain this intermediate result.

It was shown previously that the ^{222}Rn production rate is calculated by:

$$P_{Rn} = C_{a,post} V_0 \lambda_{eff,post} \qquad \text{(J - 21)}$$

with $\lambda_{eff,post} = \lambda_{Rn} + \lambda_{v,post}$.

These equations for $\lambda_{eff,post}$ and P_{Rn} can be substituted into equation J-22 to obtain:

$$Q_{exch,pre} = [C_{a,post}(\lambda_{Rn} + \lambda_{v,post}) - C_{a,pre}\lambda_{Rn}] V_0 CF_1 \qquad \text{(J - 36)}$$

where we have again added in the units conversion factor. This equation is used in the spreadsheet.

Equations for diffusion releases. As was previously noted, the diffusion release rates are calculated as:

$$Q_{diff} = JA \qquad \text{(J - 27)}$$

where

$$J = \frac{E_c \lambda_{Rn} L_c C_a}{\sinh\left(\frac{L}{L_c}\right)} \qquad \text{(J - 26)}$$

[redacted]

These two equations are combined to give:

$$Q_{diff} = \frac{AE_c\lambda_{Rn}l_cC_a\,CF_2}{\sinh\left(\frac{L(2.54\ \text{cm in}^{-1})}{l_c}\right)} \qquad \text{(J - 37)}$$

where we have inserted a units conversion factor for L and the units conversion factor for the result, CF_2. This equation is applied in the spreadsheet to both $C_{a,post}$ and $C_{a,pre}$ to obtain $Q_{diff,post}$ and $Q_{diff,pre}$. The units of the result, Q_{diff}, are Ci y^{-1}. The units of the parameters are ft^2 (per silo) for A; fraction for E_c; d^{-1} for λ_{Rn}; cm for l_c; pCi L^{-1} for C_a; and inches for L. Thus, the units conversion factor is:

$$CF_2 = (10^{-12}\ \text{Ci pCi}^{-1})(30.48\ \text{cm ft}^{-1})^2(10^{-3}\ \text{L cm}^{-3})(365.25\ \text{d y}^{-1})(2\ \text{silos}),$$

$$= 6.7866\times10^{-10}\ \text{Ci L d pCi}^{-1}\ \text{ft}^{-2}\ \text{cm}^{-1}\ \text{y}^{-1}. \qquad \text{(J-38)}$$

Equation for radon daughter releases. It was shown earlier that the releases of short-lived ^{222}Rn daughters are calculated by:

$$Q_{daught} = Q_{exch}F \qquad \text{(J - 29)}$$

This equation is directly implemented in the spreadsheet, and no units conversion is needed.

Summary of Parameter Distributions

The distributions used to represent the parameters of the calculations are summarized in Table J-9.

Table J-9. Parameter Distributions for the Monte Carlo Calculation of K-65 Silo ^{222}Rn Releases

Parameter	Units	Distribution	Descriptive statistics
$C_{a,post}$	pCi L^{-1}	normal	mean = 2.62×10^7; standard deviation = 4.1×10^6
$\Delta T/T_0$	d^{-1}	normal[a]	mean = 0.0297; standard deviation = 0.0138
$k_{v,wind}$		uniform	minimum = 1; maximum = 2
V_0	ft^3	uniform	minimum = 40,000; maximum = 62,000
A	ft^2	known[b]	value = 5300
E_c		uniform	minimum = 0.05; maximum = 0.265
λ_{Rn}	d^{-1}	known[b]	value = 0.18129
l_c	cm	uniform	minimum = 6; maximum = 23
L	cm	uniform	minimum = 3; maximum = 4
X_{bkg}	mR h^{-1}	uniform	minimum = 15.25; maximum = 96.25
X_{pre}	mR h^{-1}	uniform	minimum = 52.5 or X_{bkg}, whichever is larger; maximum = 102.5
X_{post}	mR h^{-1}	uniform	minimum = 127; maximum = 291
F		uniform	minimum = 0; maximum = 1

[a] Actually this distribution is truncated on the low side at zero.
[b] "known" indicates that a single value is used in the calculations.

As noted in Table J-9, the distribution for $\Delta T/T_0$ is truncated at zero. This is accomplished in the spreadsheet manually, by choosing a new random number to replace those which result in negative values of $\Delta T/T_0$.

Results

Results of intermediate values of the calculations are shown in Table J-10. Two important points can be seen in this table. First, recall that equation J-10 indicates that air exchange releases are proportional to $(\lambda_v/\lambda_{eff})$. This ratio is the fraction of the total removal of Rn from the silo that occurs through ventilation, or air exchange. The difference between $(\lambda_{v,post}/\lambda_{eff,post})$ and $(\lambda_{v,pre}/\lambda_{eff,pre})$ illustrates the reason for the significant difference in air exchange releases for the two periods. For the "post" period, a significant, but small fraction of the available Rn is lost by release to the outside air. For the "pre" period, almost all of the Rn lost is through air exchange releases.

Second, the calculations indicate that, as expected based on the previous estimates, releases through the diffusion pathway are relatively insignificant compared to releases through air exchange. For the 1980–1987 period the difference of the medians of the distributions is a factor of 20. For the 1959–1979 period, the difference is a factor of about 800.

Table J-10. Summary of Frequency Distributions of Intermediate Calculated Parameters

	Percentiles of distributions				
Parameter (units)	5th	25th	median	75th	95th
$(\lambda_{v,post}/\lambda_{eff,post})$	0.061	0.14	0.19	0.25	0.31
P_{Rn} (pCi d^{-1})	5.8×10^{12}	7.1×10^{12}	8.3×10^{12}	9.7×10^{12}	1.2×10^{13}
$\lambda_{v,pre}$ (d^{-1})	0.33	0.71	1.3	2.9	14
$(\lambda_{v,pre}/\lambda_{eff,pre})$	0.64	0.80	0.88	0.94	0.99
$C_{a,pre}$	4.3×10^5	1.9×10^6	3.9×10^6	6.7×10^6	1.2×10^7
$Q_{exch,post}$ (Ci y^{-1})	320	780	1100	1600	2500
$Q_{diff,post}$ (Ci y^{-1})	7.7	24	51	93	180
$Q_{exch,pre}$ (Ci y^{-1})	3300	4400	5200	6100	7800
$Q_{diff,pre}$ (Ci y^{-1})	0.44	2.3	6.6	15	46

The results of the calculations are shown in Figures J-2 through J-5 as histograms of the distribution of the predicted release rates.

The distribution of predicted releases of ^{222}Rn for the period 1980–1987 is shown in Figure J-2. The distribution can be interpreted in terms of percentile ranges. For example, with 50% probability, the ^{222}Rn release rate for this period is predicted to be between 840 Ci y^{-1} and 1700 Ci y^{-1} (25th and 75th percentiles, respectively). And with 90% probability, the ^{222}Rn release rate is predicted to be between 380 Ci y^{-1} and 2500 Ci y^{-1} (5th and 95th percentiles, respectively).

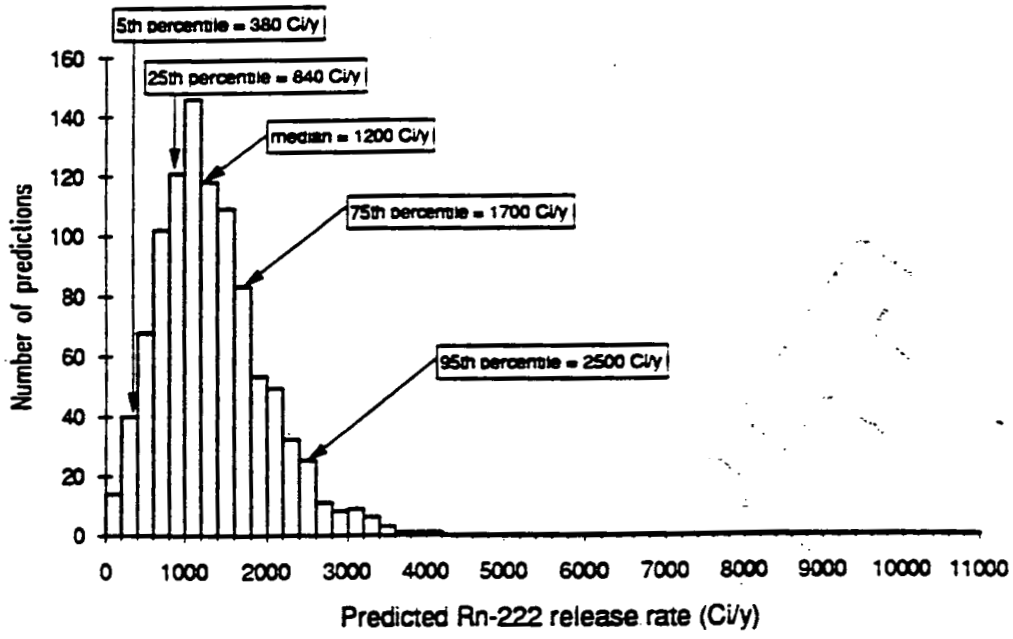

Figure J-2. Frequency distribution of predicted annual releases of ^{222}Rn for the period 1980 to 1987. The number of predictions falling within given ranges, out of the total set of 1000 predictions, are plotted against the ranges of the predictions.

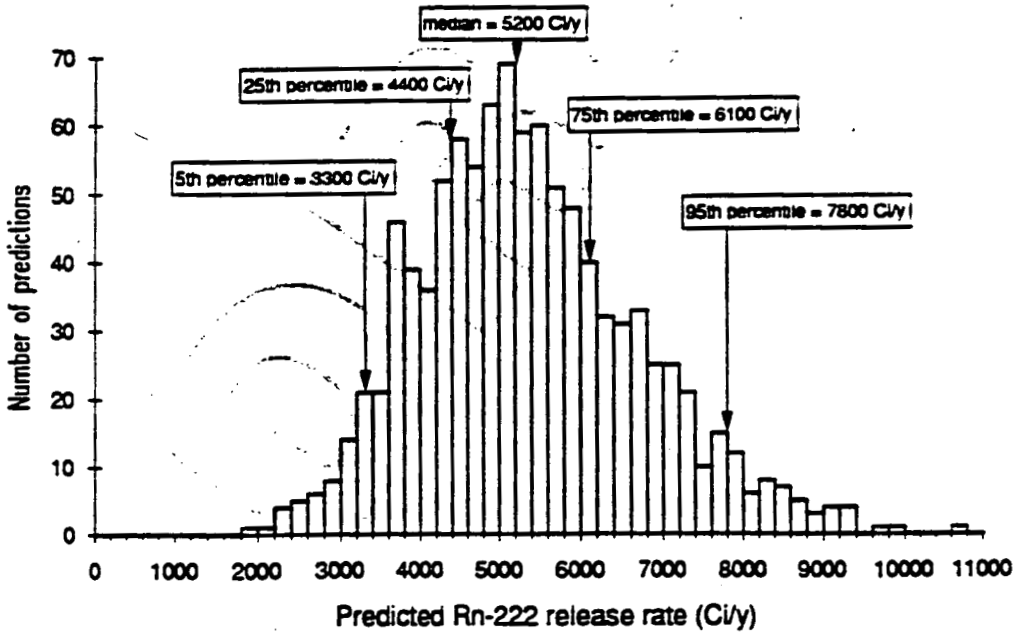

Figure J-3. Frequency distribution of predicted annual releases of ^{222}Rn for the period 1959 to 1979.

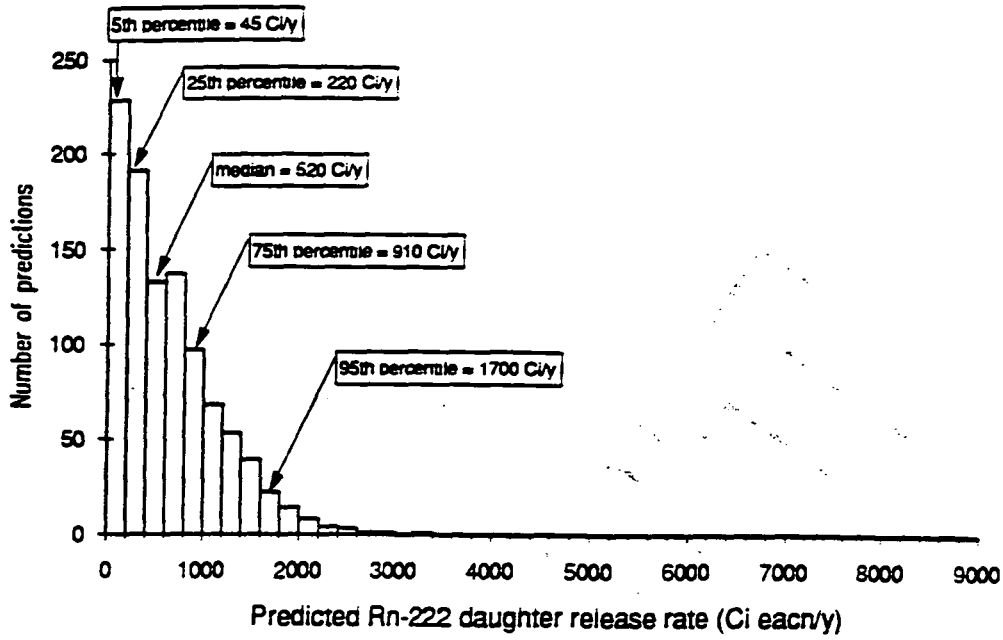

Figure J-4. Frequency distribution of predicted annual releases of ^{222}Rn daughters for the period 1980 to 1987. The number of predictions falling within given ranges, out of the total set of 1000 predictions, are plotted against the ranges of the predictions.

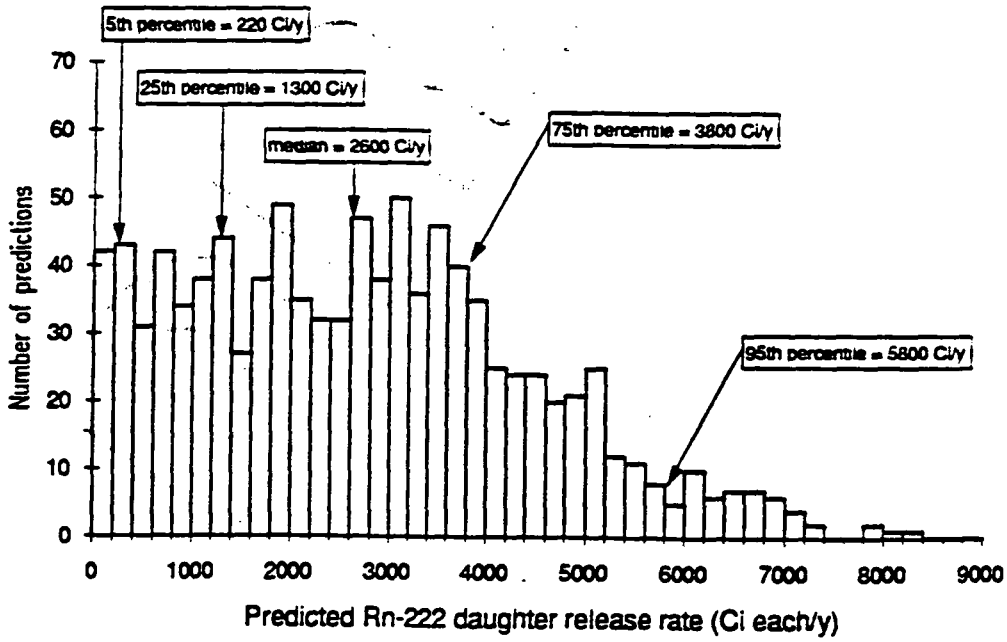

Figure J-5. Frequency distribution of predicted annual releases of ^{222}Rn daughters for the period 1959 to 1979.

The distribution of predicted releases of ^{222}Rn for the period 1959–1979 is shown in Figure J-3. With 50% probability, the ^{222}Rn release for this period is predicted to be between 4400 Ci y^{-1} and 6100 Ci y^{-1}. And with 90% probability, the ^{222}Rn release rate is predicted to be between 3300 Ci y^{-1} and 7800 Ci y^{-1}.

The distribution of predicted releases of the short-lived ^{222}Rn daughters, ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po, for the period 1980–1987 is shown in Figure J-4. With 50% probability, the ^{222}Rn daughter release for this period is predicted to be between 220 Ci y^{-1} and 910 Ci y^{-1}, for each daughter. And with 90% probability, the ^{222}Rn daughter release rate is predicted to be between 45 Ci y^{-1} and 1700 Ci y^{-1}.

The distribution of predicted releases of the short-lived ^{222}Rn daughters for the period 1959–1979 is shown in Figure J-5. With 50% probability, the ^{222}Rn daughter release for this period is predicted to be between 1300 Ci y^{-1} and 3800 Ci y^{-1}, for each daughter. And with 90% probability, the ^{222}Rn daughter release rate is predicted to be between 220 Ci y^{-1} and 5800 Ci y^{-1}.

The results of these calculations are also summarized in Table J-11. These release rates were calculated to be the rate over the full time periods ("pre" and "post") assessed. Thus, the quantities estimated to be released for the 1960–1962 period are simply the appropriate values from this table multiplied by 3 y. This applies to the various percentiles of the distributions, since the parameter distributions are applied to the full time periods, rather than independently to each year.

Table J-11. Summary of Predicted ^{222}Rn and ^{222}Rn Daughter Release Rates

Period, statistic	^{222}Rn (Ci y^{-1})	^{222}Rn daughters[a] (Ci y^{-1})
1959–1979		
5th to 95th percentile (90% probability)	3300–7800	220–5800
median	5200	2600
1980–1987		
5th to 95th percentile (90% probability)	380–2500	45–1700
median	1200	520

[a] The release quantities for ^{222}Rn daughters are quantities of each of the short-lived daughters ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po.

Conclusions

As shown in Figures J-2 through J-5 and Table J-11, the uncertainties in some of the release rates are quite large. In particular, the 90% probability interval of the ^{222}Rn releases for the period 1980–1987 has a range of a factor of almost 7. The 90% probability intervals of the ^{222}Rn daughter releases have ranges of factors of about 30 and 40 for the periods 1959–1979 and 1980–1987, respectively. For the calculations of Rn releases, the most important contributors to the uncertainties are the lack of complete information about $\lambda_{v,post}$, for the 1980–1987 period, and the limited, indirect information about $C_{a,pre}$, for the 1959–1979

period. One goal of the continuing development of the historical source term will be to reduce the uncertainty of these predictions. We will focus more of our efforts on those parameters contributing the most uncertainty to the results.

Even with the large associated uncertainties, it is clear that the releases of ^{222}Rn from the K-65 Silos was much greater in the 1959–1979 period than in the 1980–1987 period. We also note that for the 1980–1987 period the majority of the Rn released would have been released during daytime hours, when the warming of the silo air caused most of the ventilation of the silos. For the 1959–1979 period, however, the majority of the silo ventilation would have been caused by other phenomena, including effects of wind across the silo penetrations. Thus for this "pre" period, the time of Rn releases is expected to be more correlated with wind speeds, rather than temperature increases. These findings will be significant for the dose calculations to be performed in a later task of the Project.

We acknowledge that the estimates of Rn daughter releases are very uncertain. However, these releases may be important for estimates of doses to receptors close to the FMPC. At very close distances, exposures of people outdoors to Rn daughters may be due primarily to daughters released from the silos, since the short travel time would lead to relatively little ingrowth, along the travel path, of daughters from releases of Rn. Again, we will continue to try to improve the estimates of Rn daughter releases.

It has been recognized that the K-65 Silos also present a potential source of direct radiation exposure to people living near the Silos (see, for example, Dugan et al. 1990). The large inventory of ^{226}Ra in the Silos produces a large inventory of Rn daughters in the silo. Two of these daughters, ^{214}Pb and ^{214}Bi, along with other radionuclides present in the Silos, emit gamma radiations that are the source of potential exposures. This exposure pathway is being evaluated as part of the Fernald Dosimetry Reconstruction Project, but will be covered in a later report of the Project.

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TIM- 870

TECHNICAL INFORMATION MEMORANDUM

[redacted]

SUBJECT: RADON DIFFUSION COEFFICIENT MEASUREMENTS OF POLYURETHANE MATERIALS AND RADON ATTENUATION CALCULATION FOR K-65 SILOS

BY: K.K. Nielson
V.C. Rogers

RECEIVED
87 OCT 15 A9:38
RUST ENGINEERING

FOR: F.J. Maranda
The Rust Engineering Company
7400 Willey Road
Fernaldt, Ohio 45030

DATE: October 13, 1987

[redacted]

Rogers & Associates Engineering Corporation R A E

1. RADON DIFFUSION COEFFICIENT MEASUREMENTS

Radon diffusion coefficients were measured by Rogers and Associates Engineering Corporation (RAE) on four samples of polyurethane materials using the DOE-UMTRAP approved procedures.(1) The samples were prepared by Foam Enterprises Research in Houston, Texas, using four sample holders supplied by RAE.

The results of the diffusion coefficient measurements are reported using the Foam Enterprises Research sample identification numbers.

Sample No.	Bulk Diffusion Coefficient Value (cm^2/sec)	
7092	4.4×10^{-6}	ELASTOMER FOAM *
9039	3.8×10^{-4}	POUR ELASTOMER
7093	7.4×10^{-4}	FLEXIBLE FOAM *
6129	4.0×10^{-6}	RIGID FOAM *

* The three products proposed for K-65 project

T.T. Grumski

2. RADON ATTENUATION CALCULATIONS

[redacted]

Radon attenuation and surface flux calculations were made with the computer code RAECOM,(2) using the measured diffusion coefficients, reference values for the K-65 residues and cover composition and thickness. Source term data are as follows:

Radium Content	2×10^5 pCi/g
Density	1.6 g/cm^3
Emanating Power	0.2
Porosity	0.3

The cover configuration and calculated surface flux values are:

Material	Center Section Thickness (cm)	Edge Section Thickness (cm)
K-65 Source	G.T. 150	G.T. 150
7092 Material	5	5
9039 Material	61	61
7093 Material	91	183
9039 Material	213	0
Surface Flux (pCi/m^{2}s)	Center: 2.4×10^{-8}	Edges: 1.6×10^{-3}

[redacted]

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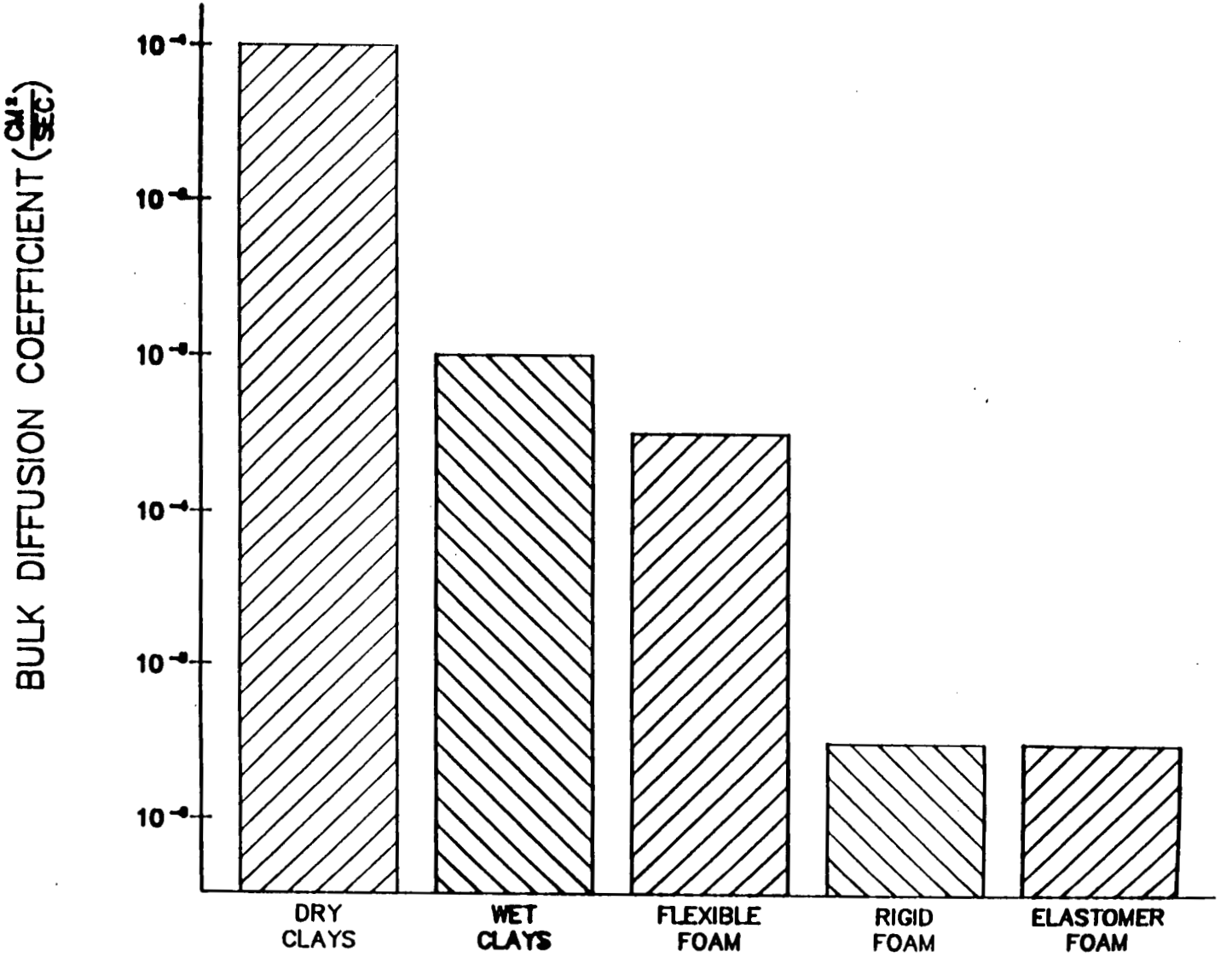
2. V.C. Rogers, K.K. Nielson, and D.R. Kalkwarf, "Radon Attenuation Handbook for Uranium Mill Tailings Cover Designs," NUREG/CR-3533, April 1984.

COMPARISON OF BULK DIFFUSION COEFFICIENTS FOR RADON



DATA SUPPLIED BY ROGERS AND ASSOCIATES ENGINEERING CORPORATION