DRAFT

A Second White Paper Addressing Enhanced Radon Releases from the K-65 Silos at the Fernald Site

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LIST OF EXHIBITS

1.0 RELEVANT BACKGROUND INFORMATION

On January 29, 2010, the Fernald Work Group met in Cincinnati, Ohio, to discuss/resolve six outstanding issues pertaining to the Fernald site. Among the unresolved issues was SC&A's contention that radon releases from the K-65 Silos may have been significantly underestimated by NIOSH, as stated in ORAUT-TKBS-0017-5 (ORAUT 2004):

> *As previously stated, the contents of the silos have not been disturbed during storage to any large degree. However, it has been calculated that during the* ***1953 to 1978 period 5,000 to 6,000 Ci/year of ^{222}Rn were released from the silos (RAC 1995)****.* [Emphasis added.]

In a previous White Paper issued in November 2008 (SC&A 2008), SC&A conducted a critical review of the Radiological Assessment Corporation 1995 model (RAC 1995). Based largely on empirical measurements taken on top of the silos that ironically were included in Appendix J of the 1995 RAC Study, SC&A concluded that the **modeled** release estimates cited in the 1995 RAC Study were likely a factor of 10 to 20 too low.

In a memorandum to the Work Group Chairperson, Mr. Brad Clawson, dated October 6, 2009, NIOSH rejected SC&A's analysis and conclusions with the following statements:

> *NIOSH disagrees with the draft findings reported by SC&A. The* ***RAC model was supported by a National Academy of Sciences review; SC&A's was not****. NIOSH will rely upon the individual exposure estimates produced using the* ***Pinney/ Hornung model*** *which utilized radon exposure levels from the RAC study, plus an additional radon source term at Fernald.* . . . [Emphasis added.]

In response to NIOSH's position, the Work Group directed SC&A to review the National Academy of Sciences' (NAS) review of the 1995 RAC model (NAS 1994).[1] On January 26, 2010 (or three days before the Work Group meeting held on January 29, 2010), SC&A submitted its findings regarding the NAS review to the Work Group/NIOSH in the form of a memorandum. Our review of the NAS Report showed that there was little support for the RAC model.

[1] Note that the National Academy of Sciences performed their review on a 1993 draft of the 1995 RAC report.

2.0 DISCUSSION POINTS RAISED DURING THE FERNALD WORK GROUP MEETING HELD ON JANUARY 29, 2010

A review of the Work Group's transcript shows that the issue of radon emissions from the K-65 Silos was discussed on pages 266 through 294 (NIOSH 2010). For convenience, select statements contained in the transcript will be cited below for further discussion.

<u>Regarding the "NAS Endorsement" of RAC (1995) Model</u>: (pp. 278–279 of transcript)

> ***MR. ROLFES****: Okay. Looking at the National Academy of Sciences' review, it's got a -- I'm reading from the National Academy of Sciences' review of the RAC dose reconstruction for Fernald, and on page 17 of the PDF, it has a radon section, and I can read that if you'd like.*
>
> *DR. MAURO: Is that what you're reading now?*
>
> ***MEMBER ZIEMER****: I'm reading it right now, yes.* ***It certainly leaves the question open.***
>
> ***MR. ROLFES****: I'll go ahead and read that into the record. "The importance of the radon source term associated with the K-65 silos is difficult to establish primarily because the silos have been modified several times over the years. If the head space has been adequately sampled, the silos inventory could be modeled for release,* ***assuming no retardation by the cap which has been sealed to various degrees over the years as a worst case endpoint****.*
>
> *"It is reasonable to separate the calculations into daytime and nighttime dispersion because the dispersion figures would certainly differ. However, there is no justification given for the release terms of 140 curies per year continuous or 810 curies per year during the daytime only. It also might be a reasonable refinement to have transition periods in between."*
>
> *So I think that's really the part that is relevant, and* ***it basically calls into question what the release is, and so the RAC report doesn't really get us any further down the road on, you know, validating the radon releases****. . . .* [Emphasis added.]

From these statements, SC&A concludes that neither the Work Group nor NIOSH is of the opinion that the NAS concurred with the RAC (1995) model.

2.1 REGARDING THE USE OF THE "PINNEY STUDY" AS A MEANS FOR THE VALIDATION OF RADON RELEASES

The "Pinney Study" was referenced multiple times in the Fernald Work Group transcript and is a reference to a study that was published in 2008 entitled, *Estimation of Radon Exposure to Workers at the Fernald Feed Materials Production Center 1952–1988*, by R.W. Hornung, S.M. Pinney, J. Lodwick, G. Killough, D.E. Brewer, and J. Nasuta in the Journal of Exposure Science and Environmental Epidmiology, pages 1–12 (Hornung et al. 2008).

<u>From page 291 of the transcript</u>:

> ***MR. MORRIS****: Okay. I'd like to also point you to a memo that Dr. Pinney wrote to* [redacted] *on September 13th, 2006, while* [redacted] *was preparing information for the SEC petition apparently, and she writes to* [redacted] *about using the data from the RAC report which was an off-site dosimetry model and extending it, extrapolating it back toward the source term to reconstruct the doses on the site. She got assurance from the model developer, Dr. Killough or Mr. Killough, that it could be extrapolated back on-site, and then took the initial action that she describes of validating that model based on some on-site information that was available. . . .* [Emphasis added.]

<u>From page 293 of the transcript</u>:

> ***MR. ROLFES****: Right. That seems that the Pinney model has the validation of the RAC model essentially in it, and what we had previously said had been reviewed by the National Academy of Sciences, when the RAC model was reviewed by the NAS, we thought that it had spoken to the radon effluent, but it didn't very much, and now what we have here when we look back at the documentation we have,* ***we found that the Pinney model actually relies upon the RAC model, which has been validated by Susan Pinney's model as well****.* [Emphasis added.]

These statements lack clarity and appear contradictory, inasmuch as they suggest that Pinney "relied" upon the RAC model, but then states that it was "validated" by the "Susan Pinney Model."

<u>From page 300 of the transcript</u>:

> ***CHAIRMAN CLAWSON****: Well, you know, the bottom line comes down to* ***SC&A has not been able to see this****, and we've got to go back a little ways because this was held up to us as the holy grail for the radon and that everything was good with it, and now we've changed our whole course to that. So we're going to have to have SC&A review what NIOSH has put out there, the* ***Pinney report****, and so forth because, you know, we're changing whole directions.*

MR. ROLFES: That's a slightly different -- ***we've always said since our Evaluation Report that we were relying upon the Pinney data.*** *So I did want to point that out.* [Emphasis added.]

2.2 REVIEW COMMENTS AND RELEVANT CONCLUSIONS REGARDING THE "PINNEY REPORT"

At the request of the Fernald Work Group, SC&A reviewed the 2008 "Pinney Report" (Hornung et al. 2008) with regard to its use/validation of radon releases that were modeled by RAC. Based on our review, SC&A concludes the following:

(1) The Pinney Report simply accepted the source term releases of radon from the K-65 Silos, as described by the following two RAC reports issued in 1995 and 1998:

- RAC (1995): *The Fernald Dosimetry Reconstruction Project, Tasks 2 and 2 Radiologic Source Terms and Uncertainties.*

- RAC (1998): *The Fernald Dosimetry Reconstruction Project, Task 6 Radiation Doses and Risks to Residence from FMPC Operations from 1951–1988.*

(2) Using the modeled RAC (1995)/RAC (1998) radon release source terms, the "Pinney Report" investigators applied a modified Gaussian dispersion model originally intended for estimating exposure to residents living within a 10-km radius to estimate onsite radon exposures to Fernald workers, as explained in their report:

<u>From page 2 of the 2008 "Pinney Report"</u>:

The radon dispersion model was developed by Radiological Assessments Corporation (RAC) under contract to the CDC as part of the overall dose reconstruction that also included uranium and thorium doses from air and water transport. The model had been applied to the estimation of radon exposures to residents living near the facility. ***Details of the development of this model are given by Voilleque et al . (1995)*** **[RAC 1995]** ***and Killough et al. (1998)*** **[RAC 1998]** ***and are beyond the scope of this paper****. We have, however, included an abbreviated description of the* **atmospheric dispersion model in Appendix A***. The model was studied to determine what revisions would be required to make it applicable to the estimation of radon exposures to Fernald workers who were considerably nearer to the K-65 silos.* ***The radon transport model involved emission rates from the silos, meteorological data, distance from the source, and decay rates of radon decay products****. The output of the model was annual average exposure in either pCi/l or Bq/m^3 at any location specified by longitude and latitude coordinates. . . .* [Emphasis added.]

From Appendix A of the 2008 Pinney Report:

> *The K-65 source term model is an empirical representation of the annual release of radon from the K-65 silos from 1952 through 1988. It was calibrated to a variety of data, primarily (1) the concentration of radon in the silo headspace gas, measured in* ***1987****, (2) measurements of g-ray exposure on the external silo dome surfaces before and after they were sealed, and (3) a series of temperature and pressure readings in the silo headspace gas, taken in 1987. It is a stochastic model, with some parameters derived as probability distributions, which propagate into the annual release estimates.* ***Detailed information about the K-65 source term model and the ratio of decay products at the point of release is given in Appendix Q of Killough et al. (1998)*** **[RAC 1998],** ***with references to the earlier report of Voilleque et al. (1995)*** **[RAC 1995]** ***for some details.***
>
> *. . . The transport model used for the study described in this paper is adapted from the transport model of Killough and Schmidt (2000),* ***but it is coupled with the original K-65 source term developed for the CDC dose reconstruction study, as described in Appendix Q of Killough et al. (1998)*** **[RAC 1998]** ***and in Voilleque et al. (1995)*** **[RAC 1995]**. [Emphasis added.]

This last statement clearly states that the "Pinney Model" simply " . . . coupled the original K-65 source term . . .," as defined in RAC 1995 and RAC 1998, to the radon transport model employed by the "Pinney Model." Thus, contrary to NIOSH's opinion, the "Pinney Report" made no effort to validate the radon source terms defined in RAC 1995 and RAC 1998.

2.3 OVERVIEW OF THE RAC MODELS

As already noted above, the 1995 Voilleque et al. study represents the RAC (1995) study, which was referenced by NIOSH in the Fernald Site Profile (ORAUT-TKBS-0017-5), and was the principal source of information for SC&A's previous White Paper issued in November 2008 (*An Alternative Assessment of Radon Release from K-65 Silos*) (SC&A 2008).

In 1998, the 1995 RAC Report was updated/modified. The revised report included (1) a brief description of the **conventional model** that had been described in Appendix J of the earlier 1995 RAC study, and (2) an updated model that was termed the **preferred model** that was described in Appendix Q of RAC (1998).

The following excerpts from the 1998 RAC report summarize the earlier **conventional model** and the updated **preferred model**:

From Vol. 1, pages 23 and 27, of RAC 1998:

> *Appendix J of our Task 2/3 report (Voilleque et al. 1995)* [RAC 1995] *described the radon releases in considerable detail; much of the following information is summarized from that appendix. . . .*

> *There are **no direct** measurements of release quantities for radon and radon decay product releases . . . The most important data sets for reconstructing the radon releases . . . are discussed in the Task 2/3 report (Voilleque et al. 1995)* [RAC 1995] *and in Appendix Q of this report (Volume II).*
>
> ***Because of the limited availability of data, models were used to estimate the quantities of radon and radon decay products that were released.** A **conventional** model for estimating radon releases from radium-226-bearing material involves calculating the quantity of radon formed in the material and the subsequent diffusion of the radon through the material to the outside air. The **conventional model** was not the primary model employed in this study because site-specific measurements of the radon diffusion coefficient and radon emanation fraction had not been made. Instead, our **preferred method** was to develop and adapt other models to calculate air exchange, diffusion, and total radon releases from the data that were available. **Figure 15** compares our **preferred method** to the **conventional method**. The **conventional method** was used for a secondary calculation to provide a limited check of our primary calculation. . . .* [Emphasis added.]

For convenience, "Figure 15" cited above is reproduced herein as Exhibit 1. Of significance are statements that acknowledge the limitations and high uncertainties of these models.

Revised estimates of annual release rates for the **preferred method** are cited by RAC (1998) in Figure 16 and reproduced herein as Exhibit 2. Figure 17 (reproduced herein as Exhibit 3) presents a comparison between release estimates derived in behalf of the RAC (1998) **preferred method** and the RAC (1995) **conventional method**. According to the authors of the two RAC reports, while the addition and/or refinements of model parameters only modestly affected the median values, there was a significant reduction in the uncertainty of release rates.

Inspection of Exhibit 3 also shows that, in addition to RAC's **preferred method** estimates and its **conventional method** estimates, the authors identified yet a third method, referred to as the **concentration-based minimum unconstrained release rate**, shown by the gray band. The issue of "unconstrained" will be discussed in greater detail in Section 3.1 below.

Exhibit 1: Figure 15 from RAC 1998

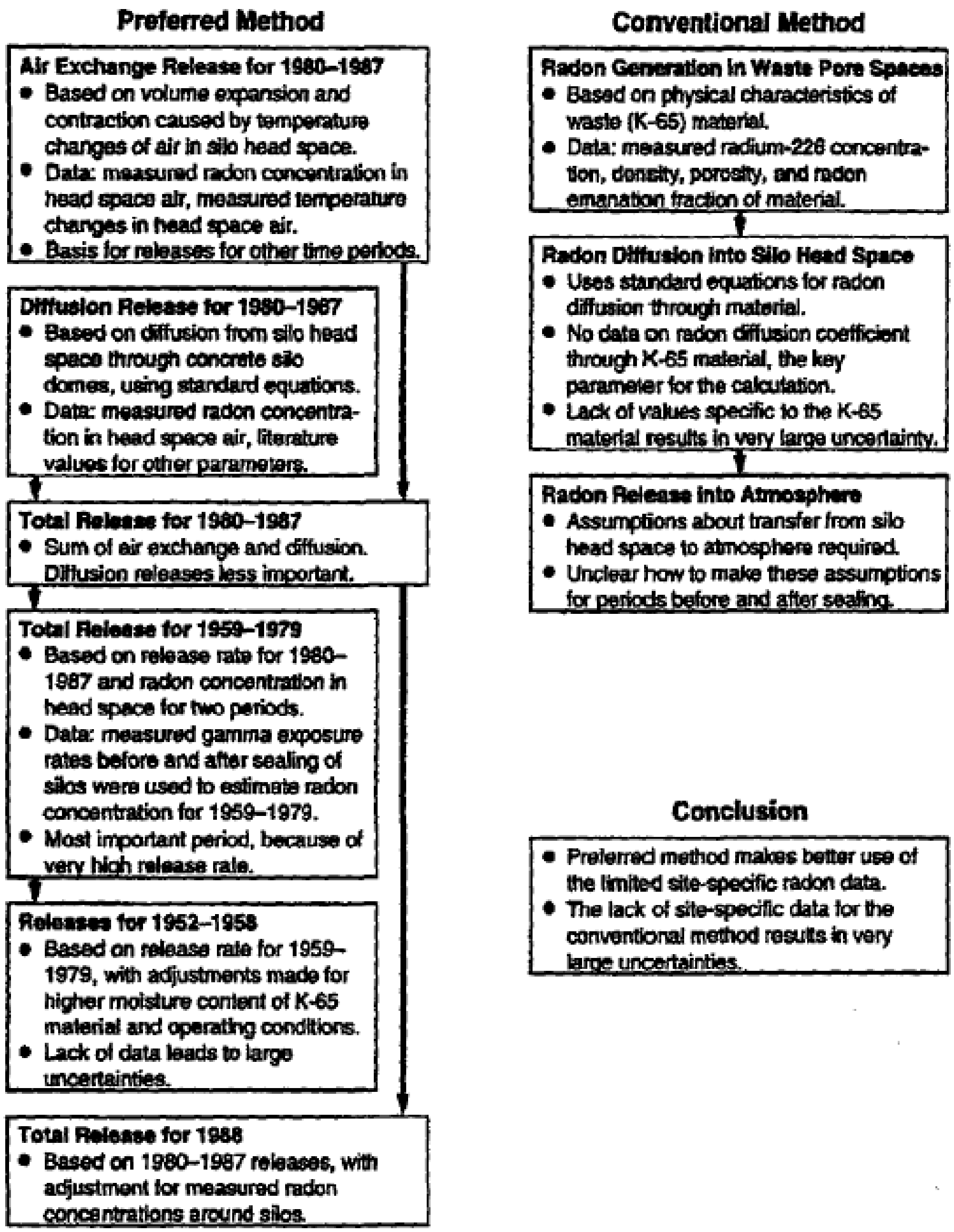

Figure 15. Comparison of the preferred and conventional methods for calculating radon releases from the K-65 silos.

Exhibit 2: Figure 16 from RAC 1998

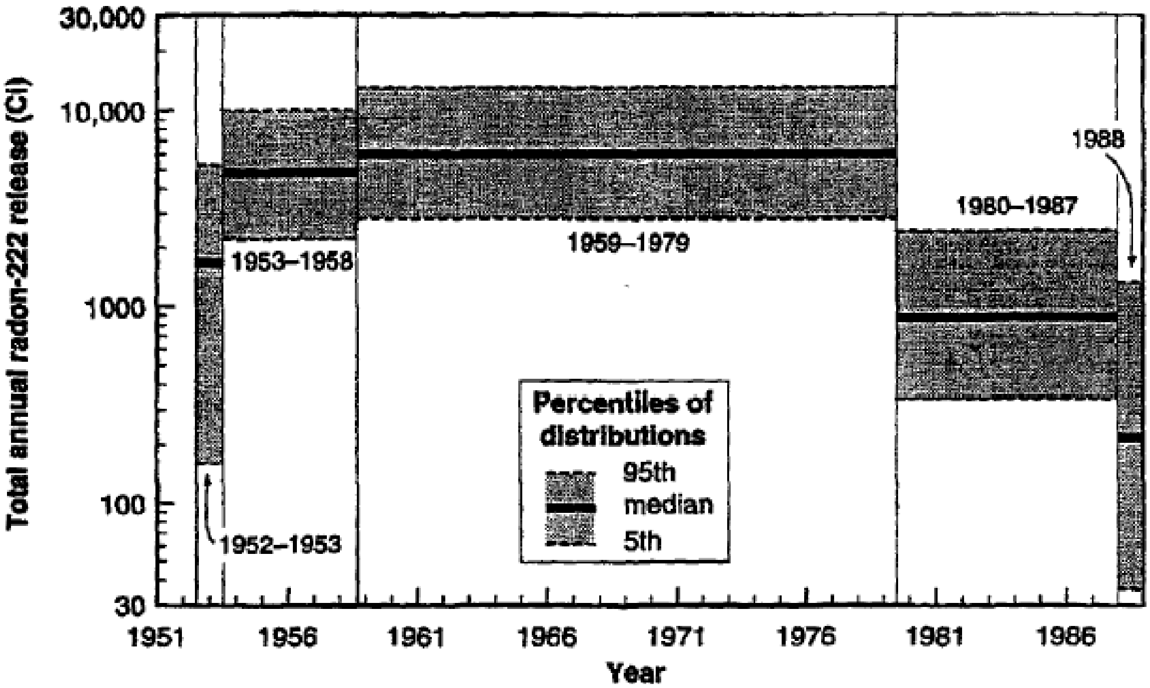

Figure 16. Changes in the estimated radon releases rates from the K-65 silos with time. The gray band shows the 90% probability interval. The solid centerline represents the median release rate, bounded by the 95th percentile (upper dashed line) and 5th percentile (lower dotted line). The 1959–1979 period is the most important with a very high release rate for a long period of time. The sealing of penetrations of the silo domes in 1979 resulted in a significant decline in radon emissions. The addition of an exterior foam layer on the silo domes in 1987 further reduced the emissions of radon. Note the logarithmic scale for annual releases.

Exhibit 3: Figure 17 from RAC 1998

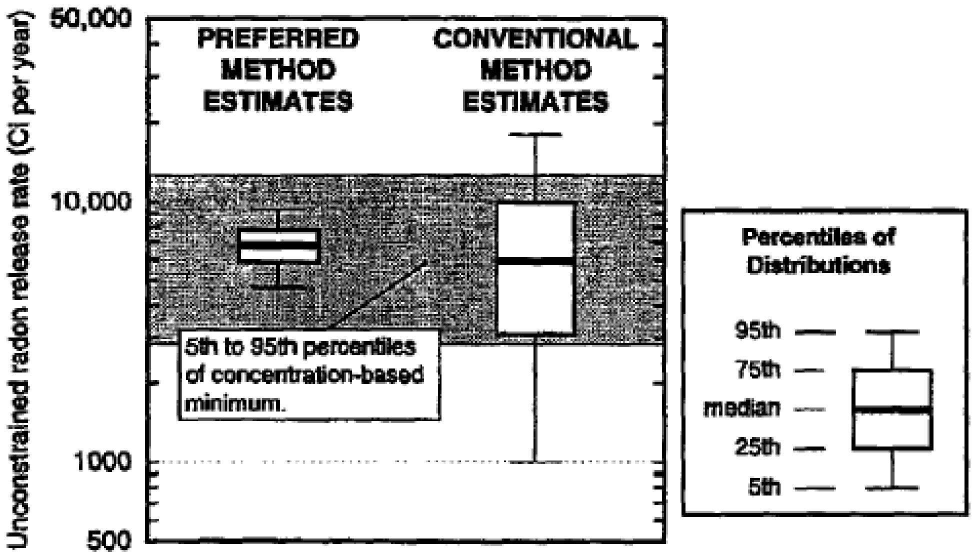

Figure 17. Comparison of estimated unconstrained radon releases from the K-65 silos using three methods: (1) our preferred method (our primary calculations), (2) the conventional method (used as a check), and (3) a concentration-based minimum unconstrained release rate, shown by the gray band. The unconstrained radon release rate is the release rate estimated to occur if the K-65 material were open to the atmosphere. The concentration-based minimum release rate is the minimum required to sustain the radon concentration in the silo headspaces (this concentration was measured in 1987). The gray band is the estimated 90% probability interval (5th to 95th percentile band) of this minimum. The conventional-method estimates that are less than the concentration-based minimum are inconsistent with the measured head space radon concentration. Note the logarithmic scale.

3.0 OTHER DATA IDENTIFIED BY NIOSH FOR SC&A'S REVIEW

During the January 29, 2010, Fernald Work Group meeting, NIOSH also identified the following two studies to SC&A with the expectation that these studies would further challenge SC&A's claim for enhanced radon emissions from the K-65 Silos:

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

- Hagee, G.R., P.H. Jenkins, P.J. Gephart, and C.R. Rudy, 1985, *Radon and Radon Flux Measurements at the Feed Materials Production Center, Fernald, Ohio*, U.S. Department of Energy, MLM-MU-85-68-001.

Presented below are summary descriptions of these two studies, with focus on issues salient to radon release estimates from the K-65 Silos.

3.1 REVIEW OF STUDY #1: KILLOUGH AND SCHMIDT (2000)

Important to note here is that the two authors of this study (i.e., Killough and Schmidt) were also co-authors of the two previous RAC (1995) and RAC (1998) studies. Thus, in addition to the "Preferred Method" estimates, the "Conventional Method" estimates, and the "Concentration-based Minimum Unconstrained Release Rate Method" described in RAC (1998), yet a fourth method was proposed by these authors, which they termed "Empirical Release Model." The fourth "Empirical Release Model" was described in Section 2.1 of their report and provides the following explanation:

> *2.1. The release model*
>
> *The model for release of radon and its decay products that was used in the dose reconstruction study is based on measurements, material balance, and other physical assumptions.* ***The details, which are somewhat complicated, are given elsewhere (Voilleque et al., 1995; Killough et al., 1998)*** **[RAC 1995; RAC 1998],** ***and we hope to submit a summary for the open literature****. We provide here a simpler counterpart of the release model, which mimics the original adequately for our purpose. This imitation was derived by Monte Carlo methods, using the authentic model to generate 1000 sets of releases and estimating parameters of the relevant distributions from the resulting data. In this paper, we call the radon release model derived in this fashion "empirical" because it consists of a joint distribution that is based on sampling the output of the* ***original model****. Before giving details of the empirical model, it is necessary to explain how the releases changed over time during the operation of the plant.*
>
> *The years 1952–1988 are divided into five major periods, corresponding to changes in the structure or operation of the K-65 silos. These periods are 1952, 1953–1958, 1959–1979, 1980–1987, and 1988. During the first two*

periods, the silos were being filled. The third period corresponds to releases at the highest annual rate. The fourth period represents the time after the silo domes were sealed in 1979. In December 1987, a layer of foam was added to the silo domes, further reducing the release rate, and hence 1988 is considered a distinct period. The dose reconstruction project's temporal scope ended with 1988.

During each major release period, it is assumed that the release rate for radon is constant with time. Thus the release for each year of a given period is the same, but the annual rate varies from one period to another. [Emphasis added.]

For the time between 1959 and 1979 (which coincides with the time period of concern to SC&A), Killough and Schmidt (2000) derived an annual release estimate of 5.41 TBq, which corresponds to **146 Ci**.

In spite of their claim that the **empirical release model** was based on ". . . details, which are somewhat complicated [and] are given elsewhere (Voilleque et al., 1995; Killough et al., 1998)," their new estimate was more than 40 times lower than the median estimates of around 6,000 Ci cited in Voilleque et al. 1995, (i.e., RAC 1995), and Killough et al. 1998, (i.e., RAC 1998).

In Section 4.0 of this report, SC&A identifies a common flaw that adversely limits the credibility of all four RAC models/release estimates.

3.2 REVIEW OF STUDY #2: HAGEE ET AL., 1985

In 1984, the U.S. Department of Energy (DOE) sponsored a radon and radon flux study at Fernald that focused on the K-65 Silos as the principal source terms for radon releases.

Important to note is that the time of this study **post dates the June 1979** remediation effort by 5 years. Remediation efforts included (1) the removal of a 15-cm diameter gooseneck at the top-center of the dome, (2) use of sealant gaskets for four influent manholes and one unloading manhole, and (3) use of sealant for all other visible penetrations and structural cracks. Although the results of this study have limited quantitative value to SC&A's contention of enhanced radon releases **prior to 1979**, there are, nevertheless, interesting observations/measurements that support our contention of enhanced radon releases prior to 1979.

In this study, radon flux measurements from concrete surfaces were made by means of charcoal canisters at 24 locations on top of each of the two silos. Areas selected for flux measurements included areas with "obvious cracks and fissures." For radon flux measurements, the analytical methods, instrumentation, results and their limitations are described in Section B of Hagee et al. 1985. Summarized below are key statements/data taken from Section B of Hagee et al. 1985 that are of relevance to this report.

*It was found that when alpha probes were held over some of the obvious cracks, the meters (Ludlum Model 12) were **disabled even on the least sensitive scale**.*

Likewise, substantial readings were found where metal rods and pipes protruded through the concrete surface.

From these preliminary studies, it was decided that it would be imperative to evaluate whether the rate of release of radon from some of the more serous cracks was sufficient to ***saturate charcoal canister*** [saturation was estimated at 200–250 μCi].

. . . For both of the locations investigated in this study, the 200 to 250 microcuries [of radon-222] uptake required only ***20 minutes of exposure****, which translated into elevated radon flux values. Clearly, the exposure time for these flux measurements is considerably different from the measurements of mill tailings and soil which are usually carried out over a period of several days. . . .*

In spite of the selection of the times of exposure as described above, certain canisters could not be measured immediately on the scintillation spectrometer . . . [due to] *. . . prohibitively high count rates on the spectrometer.*

[Furthermore]*, to permit the measurement of canisters with elevated gamma-ray emission rates,* ***two low-geometry*** *counting conditions were established . . . In the first condition, the canister was placed on the end of a PVC tube in a reproducible location, about 12" from the crystal. In the second condition, lead shielding with a hole of approximately ¾-inch diameter was placed on the end of the PVC tube. Condition 1 resulted in an efficiency reduction of approximately a factor of* ***20****; whereas, in Condition 2, the efficiency reduction was approximately a factor of* ***386****. . . .*

Even with reduced counting efficiency, it was necessary in a number of cases to wait as long as 8 days before analyzing certain canisters . . .

Flux values on the north tank ranged from approximately 13 pCi/m^2/sec to 3 × 10^7 pCi/m^2/sec and on the south tank from approximately 30 pCi/m^2/sec to 1.4 × 10^7 pCi/m^2/sec.

[Because] *the flux values are in pCi/m^2/sec, this assumes that the accumulated radon is coming from a* ***planar source*** *which, in the case of* ***cracks or fissures is not true****; . . .*

In another column of Table 2 the rate of radon release is expressed in pCi/cm/sec. The assumption made in this case is that the radon is coming through a single crack of undefined width whose length is equal to the diameter of the canister . . . [Emphasis added.]

As a benefit to the reader, the above-referenced Table 2 is enclosed herein as Attachment 1, which provides radon flux data for the 48 silo locations in the units of (1) pCi/m^2/sec and (2) pCi/cm/sec.

To illustrate these data, sample location #24 of the **North Tank** provides the following information (see Attachment 1):

- This sample location represented the highest measurement and involved a crack (c) that was sampled for 52 minutes.
- This resulted in an estimated **areal flux** (JA) of 2.8 (7) or 2.8×10^7 pCi/m^2/sec. This corresponds to **994 curies/m^2/yr**.
- When converted to a linear flux value (JL), the value 2.1 (4) or 2.1×10^4 pCi/cm/sec was derived. This converts to a yearly release rate of 0.66 curies per cm length of the "undefined" crack.

With a dome cap diameter of 24 meters, representing 1,810 m^2, it is clear that the flux data given in Attachment 1 have limited value for defining a collective source term for the silo. These feelings were shared by Hagee et al. 1985, who concluded the following:

> *The surfaces of the storage tanks represent a very discontinuous source. It is, therefore, **virtually impossible to employ the measured flux values to infer a source term**. The problem is compounded by the existence of **severe radon release** around most of the metal protrusions on top of the tanks which **could not be measured** by charcoal canister methods.* [Emphasis added.]

SC&A concludes that the Hagee et al. (1985) study has limited relevance to silo conditions/radon releases prior to June 1979. Nevertheless, the data/observations are highly suggestive of far greater releases prior to June 1979, as explained in Section 4.0.

4.0 DISCUSSION AND SUMMARY CONCLUSIONS

As briefly summarized above, over the years, investigators representing the Radiological Assessment Corporation (RAC) developed several **models** for estimating radon release quantities for discrete time periods. These time periods were defined by variations in silo contents and, more importantly, by physical modifications, which attempted to mitigate radon releases to the environment.

In spite of model modifications involving select parameters over the years (see Exhibit 4), a major limitation for all RAC models is the fact that all of the models principally derived radon release rates on (1) **radon concentrations** in the silo's headspace and (2) the **ventilation rate** of air/radon in the silo headspace. In turn, RAC assumed that the driving force for the headspace ventilation rate was defined by the diurnal fluctuation in ambient temperature and associated buildup of pressure within the headspace during the day's warming cycle, as given by the following statements:

From pages 30–31 of Appendix J, RAC (1995):

> *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:*
>
> $$\lambda_{V,\Delta T} = \Delta V / V_o$$
>
> *where,*
>
> ΔV = *the increased volume per day caused by rise in head-space temperature*
>
> V_o = *the initial silo air volume*
>
> *. . . it was concluded that the silos cannot hold any significant pressure and thus the increase 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.*

In brief, the RAC models and their release estimates are based on the assumption that diurnal environmental radon releases were defined by the thermal expansion and increased pressure within the silo's headspace and the resultant release of the "excess" volume to the environment.

SC&A believes that this diurnal thermal expansion mechanism is likely to represent but a small fraction of the total radon releases from the K-65 silo. What the RAC models fail to address are the two-fold impacts on silo ventilation rates imposed by the **Venturi effect** induced by wind.

Exhibit 4: Table 8 from RAC 1998

Table 8. Important Parameters in the Radon Source Term Calculations

Period	Parameters in calculation[a]
1988	● Calculated releases for 1980–1987. ● Measured radon concentrations in air around the K-65 silos.
1980–1987: air exchange releases	● Measurement of radon concentration in silo head space air. * Daily temperature change of headspace air, based on measurements. ● Volume of head space air.
1980–1987: diffusion releases	● Measurement of radon concentration in silo head space air. ● Radon diffusion length and porosity of silo dome concrete. ● Silo dome concrete thickness.
1959–1979	● Calculated releases for 1980–1987. * Measurement of radon concentration in silo head space air in 1987. ● Gamma exposure rate measurements on silo domes, before and after sealing of silos.
1952–1958	● Calculated releases for 1959–1979. * Assumed factors to account for operating conditions and moisture content in K-65 material.
All: radon decay product releases	● Calculated radon releases. ● Radon decay product equilibrium fraction in headspace air, calculated from radon kinetics.

[a] Uncertainty has been accounted for in all parameters of the radon source term calculations. Uncertainties in the parameters marked (*) contribute the most to the overall uncertainty of radon release quantities.

4.1 THE ROLE OF WIND AND THE VENTURI EFFECT

In Section 4.0 of our previous White Paper dated November 2008, SC&A had concluded the following (SC&A 2008):

> *A serious deficiency of the RAC model is its failure to properly account for the* ***Venturi effect*** *that is likely to have dominated the release of Rn-222 from the silo headspace prior to June of 1979, when the silos were subjected to major sealing modifications. The Venturi effect would have the following impact: during periods of low to moderate winds, a steady flow of air over the curved smooth surface of the silo dome creates a partial vacuum (much like that over the leading edge of a forward-moving airplane wing that creates the necessary lift for flight).*

In essence, the wind-induced Venturi effect results in the reduction of atmospheric pressure over the external surface of the dome cap relative to the atmospheric pressure within the silo's headspace. Under sustained steady wind conditions, this pressure differential not only induces a pressure-driven release of air from the silo's headspace into the environment, but in time also results in a reduction of pressure within the headspace relative to the pressure within the waste material that is the radon source term. This secondary pressure differential between the headspace and silo waste material will also result in a pressure-driven migration of radon gas from the waste material into the dome's headspace.

A review of the scientific literature related to radon in homes, buildings, and other man-made structures show that pressure-driven radon flow is the dominant mechanism. The EPA, in a 1987 document entitled, *Radon Reference Manual* (EPA 1987), stated the following (from Chapter 8):

> *. . . Radon in the soil can enter the home through two gas transport mechanisms: **molecular diffusion** (movement from an area of high concentration to low concentration at **constant pressure**) and **pressure-driven** flow (movement from a high to a low pressure area). Scientific investigators have indicated that **diffusion cannot** account for the high levels of indoor radon, but rather, pressure differences between indoor and outdoor air seem to be the **major determinant**.*
>
> *Pressure-driven flow, where radon is actually drawn into the structure, is influenced by several factors. During the heating season, indoor temperatures are often higher than outdoor temperatures, causing a tendency for warm indoor air to be displaced by cooler outdoor air. This tendency is called the **stack** effect since the warm air tends to rise as in a **chimney**. . . . **Wind** is another important factor that causes a pressure difference and drives the flow of radon . . . [and] open fireplaces also create a significant draw on indoor air. . .* [Emphasis added.]

Based on the fact that the cylindrical dome-capped silos represent a configuration that is optimally affected by wind-induced pressure differentials, it is puzzling why the RAC model excluded this important radon release mechanism, even though its authors were fully aware of its potential role and stated the following in their 1995 report:

<u>From pages J-31 and J-32 of Appendix J of RAC 1995</u>:

> *Since the silo 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 domes. For the present work, it is assumed that the silo ventilation is the **sum** of the ventilation rate due to the **temperature effects** and a ventilation rate due to **wind** effects. That is,*

$$\lambda_{V,\,post} = \lambda_{V,\,\Delta T} + \lambda_{V,\,wind}$$

However, the authors subsequently elected to ignore the potential contribution of wind-induced ventilation, as given on page J-34 of Appendix J:

> *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 $\lambda_{V,\,wind}$.*** *. . . Since additional information has not been located to substantiate a value for $\lambda_{V,\,wind}$,* ***we now assume a value of zero***. [Emphasis added.]

Furthermore, it must be noted that the above-cited comments/conclusion by the RAC authors in 1995 post date the major remediation efforts of June 1979.

It is SC&A's firm belief that prior to 1979, the wind/Venturi effect was likely the dominant mechanism for headspace ventilation and the release of radon to the environment.

- Support for high ventilation rates prior to June of 1979 and the role of the Venturi effect comes from the near-equal contact dose rate measurements taken on top of the dome **before 1979** and **after 1987** with the operation of the **Radon Treatment System** (see Exhibit 5). The following data points from Exhibit 5 illustrate our contention:

- In May 1973, contact dose rate measurements on top of Silo 2 showed values between 70–75 mrem/hr.

- In April 1980 (or post-1979 sealing of Silo openings), the contact dose rate on Silo 2 increased to 200–250 mrem/hr.

- In November 1987, contact dose rate measurements for Silo 2 **again** showed similar dose rates of 221 to 250 mrem/hr with an average of 232 mrem/hr.

- In the same period (i.e., November 1987), contact dose rate measurements on top of Silo 2 were again taken. However, this time, dose rates were taken **after the Radon Treatment System (RTS)** had been activated. With the activation of the RTS, the dose rates were reduced to 60 to 76 mrem/hr, with an average of 68 mrem/hr.

Important to note is that the dose rate in May 1973 (at 70–75 mrem/hr) is essentially equal to the dose rates of 60–76 mrem/hr obtained in 1987 with the activation of the Radon Treatment System.

Appendix J of RAC 1995 described the **Radon Treatment System**, as follows (pages J-28 to J-29):

> *The RTS was 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* [top of] *the silo dome* ***surface*** [i.e., contact] ***stopped decreasing*** . . . *With these flow rates 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. . .*
>
> *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**.* [Emphasis added.]

From these statements contained in RAC 1995, the following conclusions must be drawn:

(1) The release rates of Rn-222 (and its short-lived daughters) varied greatly over time and reflect incremental modifications to the K-65 silos aimed to mitigate the releases of Rn-222.

(2) Undoubtedly the single most important modification for reducing radon releases was the sealing of multiple penetrations that included manhole covers, a 6-inch diameter gooseneck pipe, and large numbers of cracks in June of 1979.

(3) Contact dose rate readings on top of the silos prior to 1979 are essentially identical to the 1987 contact dose rate readings taken **after the operation of the RTS**.

(4) Based on the relationship of the 1987 contact dose rate readings on top of the silo domes and reduced activity levels in silo headspace, the derived headspace ventilation rate prior to June 1979 can be assumed at 1.2/hour. Implicit in this assumption is that for years prior to 1980, there was little or **no buildup** of radon/radon daughters in the headspace of the K-65 silos as a result of unfettered radon releases to the environment.

(5) The enhanced emanation rate of Rn-222, from the contained waste into the silo's headspace and the **unconstrained** release from the headspace into the environment, limits further decay and formation of Pb-210 within the waste material. Thus, the empirical observation of disequilibrium between Ra-226 and Pb-210 (as noted in Table 5-16 of ORAUT-TKBS-0017-5) supports SC&A's contention of enhanced radon releases.

(6) Based on data presented in our previous White Paper and in this report, SC&A estimates that radon releases prior to 1980 were in excess of 100,000 Ci/yr from Silos 1 and 2.

Exhibit 5: Table J-19 from Appendix J of RAC 1995

Table J-19. Measurements of Exposure Rate (mR h^{-1}) on Domes of K-65 Silos: Before and After Sealing of Dome Penetrations

Date of Measurement	Silo	Height of Measurement	Exposure rate	Comments (reference)
		Prior to Sealing Silo Openings		
April 1964	1	contact	75	Average value, probably silo 1. (Starkey 1964)
March 1972	ns[a]	ns	30	(Levy 1972)
March 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)
July 1973	2	ns	35	Near center of dome. (Levy 1973)
ns	ns	contact	90	Specified as before sealing of openings in 1979. (Boback 1980a)
		After Sealing Silo Openings		
April 1980	1	contact	250	(Green 1980a)
April 1980	1	4 ft	150	(Green 1980a)
April 1980	2	contact	200–250	(Green 1980a)
April 1980	2	4 ft	150	(Green 1980a)
ns	ns	contact	250	Specified as after sealing of openings in 1979. (Boback 1980a)
November 1980	1	contact	175	(Green 1980b)
November 1980	1	4 ft	140	(Green 1980b)
November 1980	2	contact	85–175	The low value was near edge, rather than center. (Green 1980b)
November 1980	2	4 ft	45–100	The low value was near edge, rather than center. (Green 1980b)
May 1982	1	contact	290	(Grant and Stevens 1982)
May 1982	1	3 ft	18–250	Low value was near edge. (Grant and Stevens 1982)
May 1982	2	contact	400	(Grant and Stevens 1982)
May 1982	2	3 ft	35–280	Low value was near edge. (Grant and Stevens 1982)
April 1986	2	contact	850	Measured at crack in dome; other results not legible. (Fleming 1986)
November 1987	1	contact	168–208	Baseline, average 193. (Grumski and Shanks 1988)
November 1987	1	contact	35.5–68	After operation of RTS[b], average 55. (Grumski and Shanks 1988)
November 1987	2	contact	221–250	Baseline, average 232. (Grumski and Shanks 1988)
November 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.

REFERENCES

EPA (U.S. Environmental Protection Agency) 1987. *Radon Reference Manual*, EPA 520/1-87-20. Office of Radiation Programs, Washington, DC.

Hagee, G.R., P.H. Jenkins, P.J. Gephart, and C.R. Rudy, 1985. *Radon and Radon Flux Measurements at the Feed Materials Production Center, Fernald, Ohio,* U.S. Department of Energy, MLM-MU-85-68-001.

Hornung, R.W., Pinney, S.M., J. Lodwick, G. Killough, D.E. Brewer, and J. Nasuta, 2008. *Estimation of Radon Exposure to Workers at the Fernald Feed Materials Production Center 1952–1988*, Journal of Exposure Science and Environmental Epidemiology, 1–12.

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

NAS (National Academy of Sciences) 1994. *Dose Reconstruction for Fernald Nuclear Facility: A Review of Task 4*, National Research Council, National Academy Press, Washington, DC.

NIOSH (National Institute for Occupational Safety and Health), 2010. *Transcript of Work Group on Fernald Site Profile and SEC*. Cincinnati, Ohio. January 29, 2010.

ORAUT (Oak Ridge Associated Universities Team), 2004. *Technical Basis Document for the Fernald Environmental Management Project (FEMP) – Occupational Internal Dose,* ORAUT-TKBS-0017-5, Rev. 00, ORAUT, Cincinnati, Ohio.

RAC (Radiological Assessment Corporation) 1995. *The Fernald Dosimetry Reconstruction Project, Tasks 2 and 2 Radiologic Source Terms and Uncertainties*, prepared by Voilleque, P.G., K.R. Meyer, D.W. Schmidt, S.K. Rope, G.G. Killough, M. Case, et al., RAC Report No. CDC-5, Neeses, South Carolina.

RAC (Radiological Assessment Corporation). 1998. *The Fernald Dosimetry Reconstruction Project, Task 6 Radiation Doses and Risks to Residence from FMPC Operations from 1951–1988,* prepared by Killough G.G., M.J. Case, K.R. Meyer, R.E. Moore, S.K. Rope, D.W. Schmidt, et al. (RAC) Report No. CDC-1. Volumes I and II (final report). Neeses, South Carolina.

SC&A (S. Cohen and Associated) 2008. *An Alternative Assessment of Radon Releases from K-65 Silos*. Draft SC&A White Paper. SC&A, Inc., Vienna, Virginia.

ATTACHMENT 1: TABLE 2 FROM HAGEE et al. 1985

Table 2

SUMMARY OF RADON FLUX MEASUREMENTS MADE ON OCTOBER 24, 1984 FROM K-65 RESIDUE STORAGE TANKS, FERNALD, OHIO

North Tank

Location	Distance From Center ft.	Quadrant	Sampling Period (min.)	Condition	JA(2)	JL(3)
1	30	N/S line, north	114	I	2.2 (3)	1.6 (0)
2	20	"	115	I	1.3 (2)	9.7 (-2)
3	10	"	177	I	5.8 (1)	4.4 (-2)
3	10	"	115	I	1.3 (1)	9.5 (-3)
4	21.7	Northeast	51	C	7.5 (2)	5.6 (-1)
5	22.6	"	50	C	6.2 (2)	4.7 (-1)
6	32.6	"	51	C	2.8 (2)	2.1 (-1)
7	30	E/W line, east	117	I	1.1 (2)	8.0 (-2)
8	20	"	117	I	9.8 (1)	7.4 (-2)
9	10	"	181	I	6.4 (1)	4.8 (-2)
9	10	"	116	I	3.4 (2)	2.6 (-1)
10	21.1	Southeast	53	C	3.9 (3)	2.9 (0)
11	20.9	"	52	C	3.7 (4)	2.8 (1)
12	33.8	"	52	C	1.9 (7)	1.4 (4)
13	30	N/S line, south	117	I	4.3 (3)	3.2 (0)
14	20	"	116	I	8.4 (2)	6.4 (-1)
15	10	"	180	I	6.3 (1)	4.7 (-2)
15	10	"	116	I	1.7 (3)	1.3 (0)

ATTACHMENT 1 (Continued)

Table 2 (Cont'd)

North Tank

Location	Distance From Center ft.	Quadrant	Sampling Period (min.)	Condition	JA(2)	JL(3)
16	21.6	Southeast	182	C	7.7 (1)	5.8 (-2)
16	21.6	"	52	C	1.1 (3)	8.0 (-1)
17	23.6	"	53	C	3.1 (4)	2.3 (1)
18	29.9	"	183	C	8.3 (6)	6.2 (3)
18	29.9	"	53	C	2.5 (7)	1.8 (4)
19	30	E/W line, west	114	I	2.1 (2)	1.6 (-1)
20	20	"	114	I	7.7 (1)	5.7 (-2)
21	10	"	115	I	8.2 (1)	6.1 (-2)
22	23.2	Northwest	50	C	5.0 (2)	3.7 (-1)
23	23.4	"	52	C	6.6 (2)	4.9 (-1)
24	36.4	"	181	C	1.6 (7)	1.2 (4)
24	36.4	"	52	C	2.8 (7)	2.1 (4)

South Tank

Location	Distance From Center ft.	Quadrant	Sampling Period (min.)	Condition	JA(2)	JL(3)
25	30	N/S line, north	207	I	1.8 (2)	1.4 (-1)
25	30	"	81	I	1.6 (3)	1.2 (0)
26	20	"	84	I	1.3 (5)	9.5 (1)
27	10	"	84	I	3.1 (4)	2.4 (1)
28	23.4	Northeast	206	C	2.4 (1)	1.8 (-2)

ATTACHMENT 1 (Continued)

Table 2 (Cont'd)

South Tank

Location	Distance From Center ft.	Quadrant	Sampling Period (min.)	Condition	JA(2)	JL(3)
28	23.4	Northeast	56	C	1.4 (2)	1.0 (-1)
29	28.3	"	56	C	1.1 (4)	7.9 (0)
30	34.9	"	55	C	7.1 (1)	5.3 (-2)
31	30	E/W line, east	212	I	6.2 (1)	4.6 (-2)
31	30	"	85	I	1.6 (2)	1.2 (-1)
32	20	"	84	I	9.3 (1)	6.9 (-2)
33	10	"	83	I	2.4 (3)	1.8 (0)
34	28.9	Southeast	50	C	9.0 (5)	6.7 (2)
35	34.0	"	50	C	2.1 (5)	1.6 (2)
36	34.5	"	212	C	6.9 (6)	5.2 (3)
36	34.5	"	51	C	1.4 (7)	1.0 (4)
37	30	N/S line, south	85	I	3.3 (2)	2.5 (-1)
38	20	"	85	I	5.3 (2)	3.9 (-1)
39	10	"	85	I	1.3 (2)	9.4 (-2)
40	27.6	Southwest	209	C	1.7 (4)	1.3 (1)
40	27.6	"	52	C	8.8 (4)	6.6 (1)
41	34.7	"	52	C	3.2 (3)	2.4 (0)
42	35.0	"	52	C	2.2 (2)	1.7 (-1)
43	30	E/W line, west	80	I	2.9 (1)	2.2 (-2)
44	20	"	81	I	9.6 (1)	7.2 (-2)

ATTACHMENT 1 (Continued)

Table 2 (Cont'd)

South Tank

Location	Distance From Center ft.	Quadrant	Sampling Period (min.)	Condition	JA(2)	JL(3)
45	10	E/W line, west	208	I	3.3 (1)	2.5 (-2)
45	10	"	81	I	1.0 (2)	7.8 (-2)
46	23.2	Northwest	57	C	6.4 (3)	4.8 (0)
47	34.2	"	55	C	2.3 (4)	1.7 (1)
48	35.5	"	56	C	1.0 (2)	7.5 (-2)

North Tank

(1) I = Intact concrete, C = crack or fissures

(2) JA is Radon Flux in units of pCi/m²/sec. 2.2 (3) = 2.2 x 10^3 pCi/m²/sec

(3) JL is in units of pCi/cm/sec. 1.6 (0) = 1.6 x 10^0 pCi/cm/sec