# Memorandum

To: Work Group on Metals and Controls Corp.
From: Robert Anigstein and Carl Gogolak, SC&A, Inc.
Date: July 8, 2020
Subject: Reply to NIOSH “Metals and Controls Corp. Thorium and Welding Exposure Model”

## Background

On April 8, 2019, the National Institute for Occupational Safety and Health (NIOSH) completed a white paper (NIOSH, 2019a) in response to two concerns raised by a petitioner for Special Exposure Cohort (SEC) Petition SEC-00236, which addressed the residual period at the Metals and Controls Corp. (M&C) in Attleboro, MA: from January 1, 1968, through March 21, 1997. These concerns included assessments of workers’ exposures during welding activities and exposures to residual thorium contamination. SC&A’s review of the white paper concluded:

> We find that NIOSH has developed plausible approaches to modeling exposures of M&C workers to residual $^{232}$Th contamination and to modeling work activities related to welding. We disagree with some of the parameters and assumptions that NIOSH used to implement its approach. However, we believe that these issues can be resolved. These therefore constitute site profile rather than SEC issues. (SC&A, 2019, p. 7)

The SC&A review identified two findings and three observations. These constitute technical basis document (TBD) issues, not SEC issues: We do not believe that NIOSH is unable to assess radiation exposures of workers at M&C during the residual period; however, we disagree with some of the assumptions and modeling parameters employed in the NIOSH assessments. NIOSH (2019b) issued a response paper replying to the SC&A review. In the present memo, we will revisit the issues that we have identified in our reviews and discuss and reply to NIOSH’s responses to these issues.

## Internal Exposures to Thorium

We will first discuss our one observation and one finding regarding the NIOSH assessment of internal exposures to thorium.

### Observation 1: The uranium inventory cited by NIOSH is inconsistent with that in the source document.

NIOSH (2019b, p. 3) “acknowledges that this was a data entry error.” Since NIOSH has resolved this observation, SC&A recommends that this issue be closed.

**Finding 1: NIOSH underestimated the $^{232}$Th concentration in the sediments and residues in the pipes under Building 10, leading to an underestimate of $^{232}$Th intakes by workers performing subsurface activities.**

This finding was based on our preliminary analysis of uranium and thorium concentrations in soils on the M&C site, listed by Sowell (1985, table 6A), and uranium concentrations in pipe sediments under Building 10, reported by Weston (1996, table 1). Our analysis was patterned on the analyses described by NIOSH (2019a), even though NIOSH did not use these results in their final dose assessments. SC&A acknowledged that the analyses relied on a weak statistical correlation: our aim was to suggest an alternative method of deriving thorium-232 ($^{232}$Th) concentration in the sediments and residues in the pipes under Building 10 using measurements of residual radioactive contamination.

Sowell (1985, table 6A) listed a number of measurements of uranium-235 ($^{235}$U) in soil samples as less than a given value. SC&A (2019) interpreted that to indicate that the results were less than the lower limit of detection (LOD) and substituted a value of one-half the LOD in such cases. In a critique of our methodology, Oak Ridge Associated Universities Team (ORAUT) (2019, p. 8) stated that "there is no technical basis for this substitution." We based our method on a suggestion by Gilbert (1987, p. 178), who stated that "if only LT [less-than] values are reported when a measurement is below the LOD, the mean $\mu$ and variance $\sigma^2$ might be estimated" by one of four methods. One of these is to "replace the LT values by some value between zero and the LOD, such as one-half the LOD. . . [This] method is unbiased for $\mu$ (but not for $\sigma^2$)." Furthermore, ORAUT (2006, p. 8) stated, "Another method for handling 'less-than values' includes substituting full values as if real, half of their values, or some other reasonable value."

## *Revised SC&A model*

In view of the more detailed statistical analysis reported by ORAUT (2019), we re-examined the available data to find an alternate approach that can utilize these data to produce a scientifically valid basis for estimating $^{232}$Th levels in the Building 10 pipe residues. In contrast to the large fraction of "less-than" (LT) values reported for $^{235}$U by Sowell (1985, table 6A), measurements of $^{238}$U in 80 of the 88 samples yielded reportable values. The remaining eight values were less than the LOD of each measurement. Each of the 88 samples yielded reportable values of $^{232}$Th concentrations. However, a pairwise comparison of $^{232}$Th and $^{238}$U concentrations in the 80 samples with reportable values of both radionuclides yielded a square of the correlation coefficient, $R^2 = 0.0064$, which indicates that the measured values of the two radionuclides are essentially uncorrelated. Consequently, using paired values to derive a ratio of $^{232}$Th:$^{238}$U in soil to calculate $^{232}$Th levels in the Building 10 pipe residues would not be statistically valid.

The residual $^{232}$Th contamination in the pipe residues and in the soil both resulted from the processing and handling of $^{232}$Th at M&C; the same is true for $^{238}$U. Consequently, we postulate that, in the aggregate, the ratio of $^{232}$Th concentrations in the pipe residues to those in the soil can be estimated by equating it to the ratio of $^{238}$U concentrations in these two media, as shown in the following expression,

$$\frac{\left[{}^{232}\mathrm{Th}_p\right]}{\left[{}^{232}\mathrm{Th}_s\right]} = \frac{\left[{}^{238}\mathrm{U}_p\right]}{\left[{}^{238}\mathrm{U}_s\right]} \tag{1}$$

where,

| | | |
|---|---|---|
| $[^{232}Th_p]$ | = | concentration of $^{232}$Th in pipe residues (pCi/g) |
| $[^{232}Th_s]$ | = | concentration of $^{232}$Th in soil (pCi/g) |
| $[^{238}U_p]$ | = | concentration of $^{238}$U in pipe residues (pCi/g) |
| $[^{238}U_s]$ | = | concentration of $^{238}$U in soil (pCi/g) |

Solving equation (1) for $[^{232}Th_p]$, we obtain

$$\left[{}^{232}\mathrm{Th}_p\right] = \frac{\left[{}^{232}\mathrm{Th}_s\right]\left[{}^{238}\mathrm{U}_p\right]}{\left[{}^{238}\mathrm{U}_s\right]} \qquad (2)$$

To evaluate equation (2), we needed to assign values to each of the three terms in the right-hand side. However, there was no obvious method to select a single value that could accurately represent the wide range of measurements of each of these quantities. Instead, we derived lognormal distributions to represent each of these quantities.[1] We then used Monte Carlo methods to randomly sample from each of the three distributions. Each triad of samples resulted in a realization: a unique value of $[^{232}Th_p]$. We repeated this process 1,000,000 times, each time deriving a new value of $[^{232}Th_p]$. These values themselves constituted a probability distribution. In recognition of the uncertainty in the data and in our assumptions, we selected the 95$^{th}$ percentile value of the resulting distribution to assign a bounding value to $[^{232}Th_p]$. The derivation of the lognormal distributions from the measured radionuclide concentrations is described in the remainder of the present section of this memo.

The 88 values of $^{232}$Th concentrations reported by Sowell (1985, table 6A) were fitted to a lognormal distribution according to the guidance provided by ORAUT (2005) and the more explicit directions provided by ORAUT (2006). In brief, the data were listed in rank order by concentration. Using an Excel spreadsheet, similar to a spreadsheet furnished by Allen,[2] we calculated "the midpoint of the percentile range associated with each data point" (ORAUT, 2006, p. 8). Each value was assigned a z-score, "the inverse of the standard normal cumulative distribution" (ORAUT, 2006, p. 8), and the natural logs of the concentration were plotted against their respective z-scores. A linear equation was fitted to these data "using standard spreadsheet linear least-squares chart functions. The $R^2$ value [was] determined by the spreadsheet function" (ORAUT, 2006, p. 8). The resulting plot is shown in figure 1. The calculated $R^2$ equals 0.760, which indicates a reasonable fit.[3] The distribution parameters were derived from the linear equation: the geometric mean (GM) is the antilogarithm of the y-intercept, while the geometric

[1] During the course of this project, both NIOSH and SC&A have traditionally used lognormal distributions to represent environmental pollution data.

[2] Allen, D. (CDC/NIOSH/DCAS). GSIWGdataset.xls, attachment to "RE: New GSI distribution," personal email to Robert Anigstein, SC&A, Inc., November 30, 2012.

[3] According to ORAUT (2005, p. 8), "values [of $R^2$] as low as 0.7 are acceptable."

standard deviation (GSD) is the antilogarithm of the slope. These derived parameters are listed in table 1.

*Figure 1. Lognormal distribution of $^{232}$Th in soil*

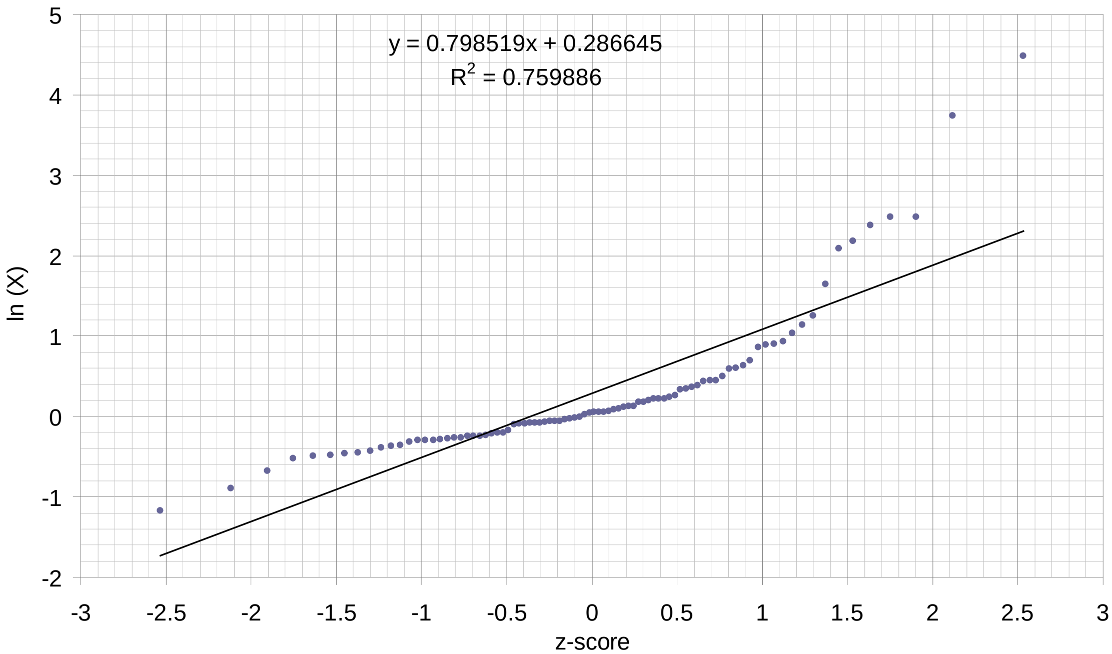



*Table 1. Lognormal distribution parameters*

| **Parameter** | **[$^{232}$Th$_s$]** | **[$^{238}$U$_s$]** | **[$^{238}$U$_p$]** | **[$^{238}$U$_s$]$^a$** |
|---|---|---|---|---|
| Intercept (μ) | 0.287 | 1.265 | 4.040 | N/A$^b$ |
| Slope (σ) | 0.799 | 1.883 | 1.651 | N/A |
| $R^2$ | 0.760 | 0.952 | 0.884 | 0.936 |
| GM (pCi/g) | 1.332 | 3.543 | 56.838 | 7.887 |
| GSD | 2.222 | 6.573 | 5.211 | 4.924 |

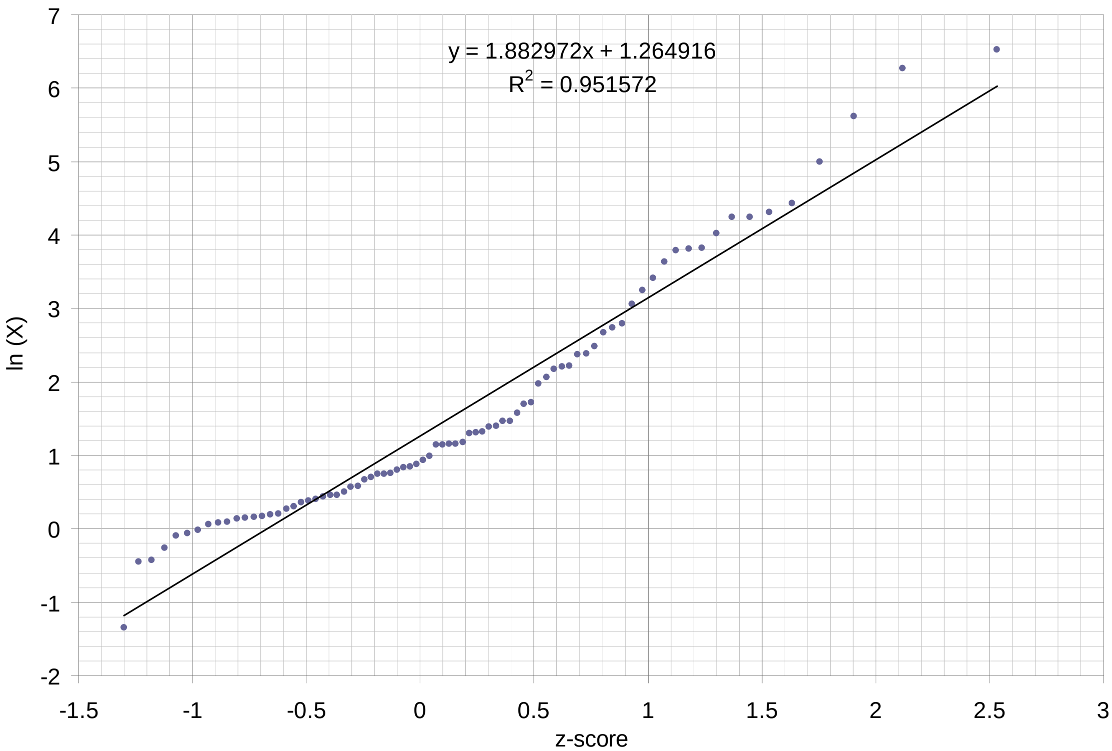
[a] Recalculated using R computer code. See “Alternate SC&A model” in the present memo.

[b] N/A = Not applicable to present analysis.

The distribution of the $^{238}$U soil samples was derived in an analogous manner. However, in this case, the 88 soil sample analyses included eight values that were below the LOD. These censored values were assigned ranks of 1–8 in the rank-ordered list of measured values but were excluded from the linear regression analysis.[4] This process is referred to as regression on order statistics (ROS). The resulting plot is shown in figure 2. In this instance, $R^2$ equals 0.952, indicating a good fit. The derived parameters are listed in table 1.

[4] According to ORAUT (2005, p. 8), “If the data are censored, rank all the data, but fit only the uncensored data.”

*Figure 2. Lognormal distribution of $^{238}$U in soil*




Finally, we used an analogous method to derive the lognormal distribution of [$^{238}U_p$]. We first ranked the $^{238}$U concentrations in each of the 18 samples taken from pipes under Building 10 (Weston, 1996, table 1), along with the cumulative volumes of pipe scale or sediment in each pipe (Weston, 1996, table 5). We then assigned each concentration to the midpoint of the respective volume element, as shown in table 2. We then derived the lognormal distribution of [$^{238}U_p$] by plotting the natural log of the concentration against the z-score derived from the corresponding normalized midpoint volume element. The results are shown in figure 3. In this instance, $R^2$ equals 0.884, indicating a reasonable fit. The derived parameters are listed in table 1.

We then used Crystal Ball (Decisioneering, Inc., 2001), a Monte Carlo Excel add-in, to solve equation (2) by sampling from the three distributions described by the parameters listed in table 1. We performed 1,000,000 simulations and obtained a distribution of [$^{232}Th_p$], with a mean of 664 pCi/g and a standard error of 12.27 pCi/g, or 1.8 percent of the mean. The 95$^{th}$ percentile equals 1,619 pCi/g. Assuming a dust loading of 220 µg/m$^3$, we obtained an airborne activity concentration of $3.56\times10^{-13}$ µCi/mL, which is 47 percent higher than the $2.42\times10^{-13}$ µCi/mL cited by NIOSH (2019a).

To illustrate the effect of such a difference, we calculated the resulting effective dose from $^{232}$Th via the inhalation pathway. If a worker with a breathing rate of 1.2 m$^3$/h were exposed for 168 h/y to such concentrations of $^{232}$Th in secular equilibrium with its progeny, the effective dose, based on the SC&A analysis and using the default dose coefficients for an occupational scenario, would be approximately 14 mrem/y, compared to 10.4 mrem/y cited by NIOSH (2019a).

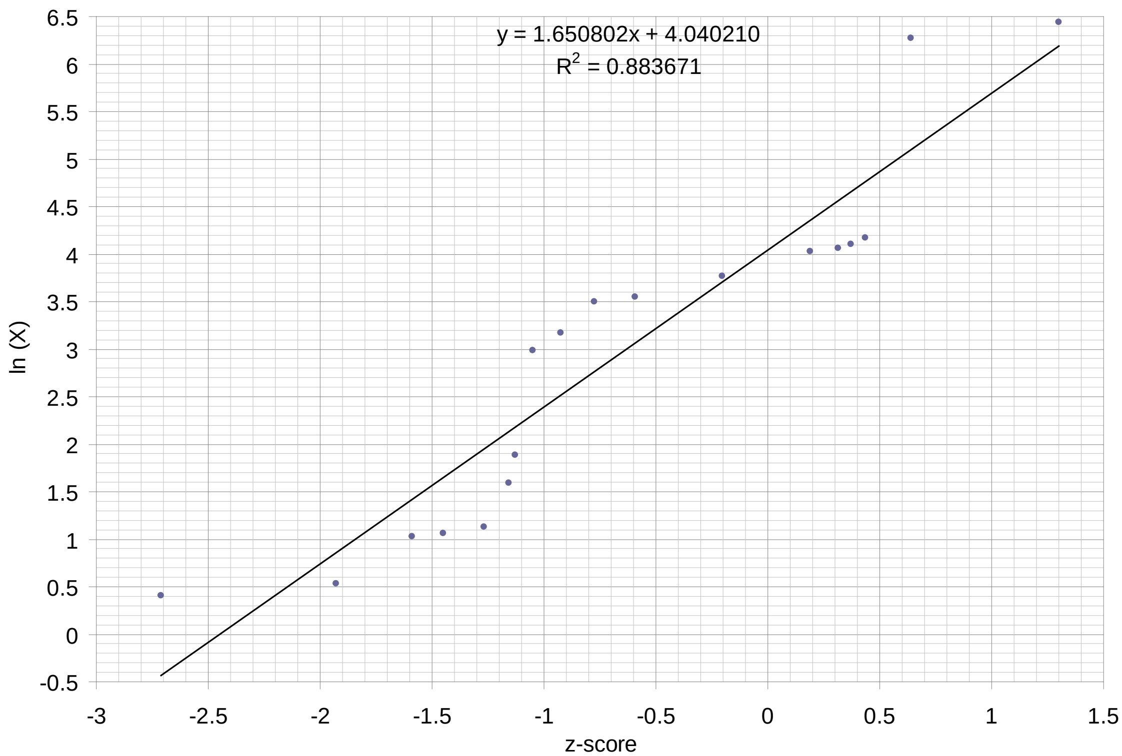
*Table 2. $^{238}U$ activity distribution in pipe sediments under Building 10*

| $^{238}U$ (pCi/g) | Volume (mL) | CVD[a] (mL) | Midpoint[b] (mL) |
|---:|---:|---:|---:|
| 1.5 | 6,178 | 6,178 | 3,089 |
| 1.7 | 37,067 | 43,244 | 24,711 |
| 2.8 | 16,062 | 59,307 | 51,276 |
| 2.9 | 16,371 | 75,678 | 67,492 |
| 3.1 | 37,067 | 112,744 | 94,211 |
| 4.9 | 1,977 | 114,721 | 113,733 |
| 6.6 | 8,031 | 122,752 | 118,737 |
| 19.8 | 24,248 | 147,000 | 134,876 |
| 23.8 | 32,124 | 179,125 | 163,062 |
| 33.1 | 43,553 | 222,678 | 200,901 |
| 34.9 | 62,087 | 284,765 | 253,721 |
| 43.4 | 200,160 | 484,925 | 384,845 |
| 56.1 | 86,180 | 571,105 | 528,015 |
| 58.1 | 2,471 | 573,576 | 572,340 |
| 60.5 | 37,067 | 610,642 | 592,109 |
| 64.8 | 6,178 | 616,820 | 613,731 |
| 529.2 | 123,556 | 740,376 | 678,598 |
| 624.7 | 177,920 | 918,296 | 829,336 |

[a] Cumulative volume distribution (CVD)

[b] CVD – ½ Vol

*Figure 3. Lognormal distribution of $^{238}U$ in sediments under Building 10*




## *Discussion of methodology*

SC&A employed the methodology recommended by ORAUT (2005, 2006) for the statistical analysis of coworker bioassay data that enabled the use of such data for unmonitored workers. There is at least one precedent for the use of such an analysis for modeling concentrations of radioactive aerosols. SC&A (2012) estimated uranium air concentrations during uranium handling operations at General Steel Industries, using data on measured aerosol concentrations at other worksites under comparable working conditions. They employed ROS methodology to estimate a 95$^{th}$ percentile uranium air concentration of 66.43 dpm/m$^3$, based on 28 data points, including eight nondetected concentrations. The measurements were made at several different worksites—the LODs for each of the nondetects were not available. This result underwent a minor change (the deletion of one data point and the inclusion of one datum previously omitted) by the action of the Work Group on TBD-6000 of the Advisory Board on Radiation and Worker Health, resulting in an adopted value of 68.7 dpm/m$^3$. SC&A, NIOSH, and the work group all agreed on the methodology used to derive this result.

## *Alternate SC&A model*

ORAUT (2014) cites a limitation of the ROS method described by ORAUT (2006) when applied to censored data "where multiple distinct decision levels are applied to the data in the dataset" (p. 10). Such was the case for the [$^{238}U_s$] data, which included eight LT values, each with a different LOD. In such cases, ORAUT (2014) recommends the methods described by Helsel and

Cohn (1988). These, or similar, methods are embodied in the function "ros," part of the R computer code package (Lee, 2020),[5] which SC&A employed in a reanalysis of the [$^{238}U_s$] data.

Function "ros is an implementation of a Regression on Order Statistics (ROS) designed for multiply censored analytical chemistry data" (Lee, 2020, p. 50). The input is a numeric vector of observations, including both censored and uncensored observations and a logical vector indicating TRUE where an observation is censored (an LT value) and FALSE otherwise.

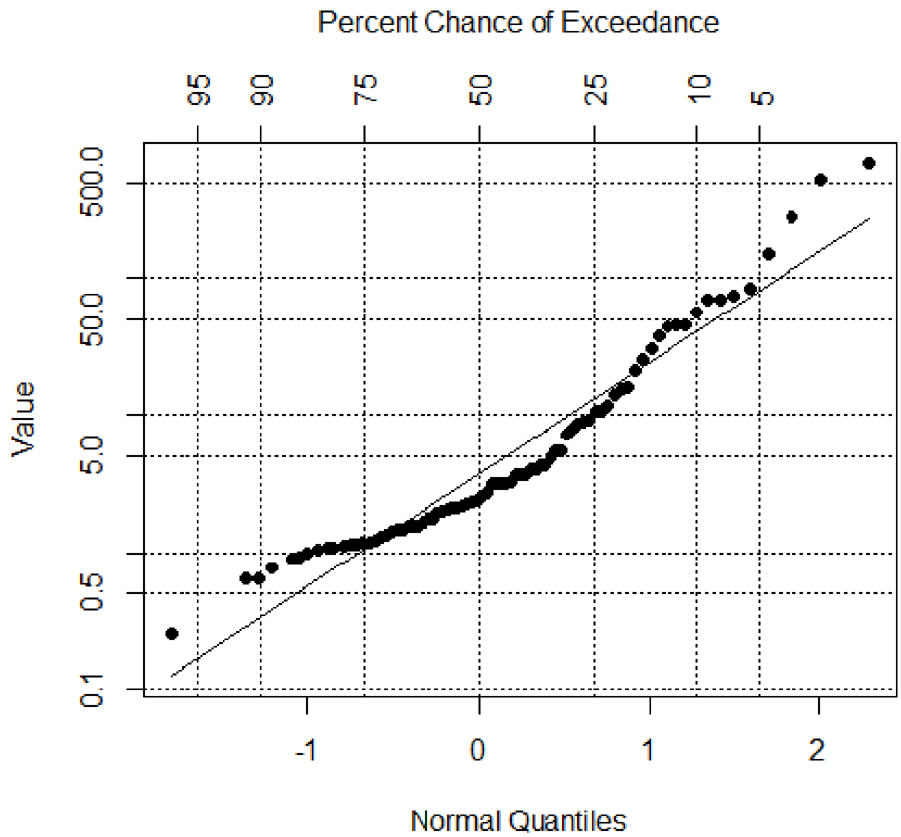
> By default, ros performs a log transformation prior to, and after operations over the data. . . The procedure first computes the Weibull-type plotting positions of the combined uncensored and censored observations using a formula designed for multiply-censored data. . . A linear regression is formed using the plotting positions of the uncensored observations and their normal quantiles. This model is then used to estimate the concentration of the censored observations as a function of their normal quantiles. Finally, the observed uncensored values are combined with modeled censored values to corporately estimate summary statistics of the entire population. (Lee, 2020, p. 50)

This function was applied to the [$^{238}U_s$] data. As stated earlier, this dataset comprised 88 observations, of which eight were left censored. The analysis yielded the following results: The arithmetic mean equals 28.10094 pCi/g and the arithmetic standard deviation equals 96.09789 pCi/g. The lognormal distribution parameters derived from these values are listed in the fourth column of table 1. The resulting plot is shown in figure 4.

As shown in table 1, $R^2$ equals 0.936 in the reanalysis of the [$^{238}U_s$] data, indicating a good fit of the data to a lognormal distribution, as was the case in our previous analysis of these data. The GM is over twice the previous value, while the GSD is somewhat smaller. We repeated the previously described Monte Carlo simulation to re-evaluate equation (2), using the new distribution of [$^{238}U_s$]. We obtained a 95$^{th}$ percentile value for [$^{232}Th_p$] of 525 pCi/g, which is less than one-third the value derived previously. Again assuming a dust loading of 220 µg/m$^3$, we obtained an airborne activity concentration of $1.16\times10^{-13}$ µCi/mL, which is 52 percent lower than the $2.42\times10^{-13}$ µCi/mL cited by NIOSH (2019a). If a worker with a breathing rate of 1.2 m$^3$/h were exposed for 168 h/y to such concentrations of $^{232}$Th in secular equilibrium with its progeny, the effective dose, based on the SC&A analysis, would be approximately 4.5 mrem/y. The use of two different methods of evaluating the distribution of [$^{238}U_s$] yields inhaled intakes of $^{232}$Th that differ by a factor of 3. The new methodology, using the R computer code, is closer to the guidance provided by ORAUT (2014), although the result is less claimant favorable.

[5] We note that the preface to the user's manual states, "Contains methods described by Dennis Helsel in his book 'Nondetects and Data Analysis: Statistics for Censored Environmental Data.'"

*Figure 4. Lognormal distribution of $^{238}U$ in soil, calculated using R computer code*




We need to keep in mind the purpose and scope of the present study: It is to demonstrate that the residual radioactive contamination data available for the M&C site can be used to derive a plausible upper bound of $^{232}Th$ intakes by workers employed in subsurface remediation activities. SC&A does not claim to have derived an exact, final value. However, we believe that our analysis shows that the data discussed in the present memo can be used for this purpose.

## Internal Exposures from Welding

We will next discuss our two observations and one finding regarding the NIOSH assessment of internal exposures from welding activities at M&C.

### Observation 2: NIOSH should clarify the source of the 4-h-per-month time estimate.

NIOSH (2019b) furnished the reference for the estimate of the duration of the welding activities. SC&A recommends that this observation be closed.

### Finding 2: NIOSH understated the resuspension factor related to activities accompanying welding.

NIOSH (2019b, p. 6) stated that

> the decision to use a resuspension factor [(RF)] of $10^{-2}$ as opposed to $10^{-3}$ is considered a TBD issue. However, NIOSH believes the assumption of a

> resuspension factor of $10^{-3}$ is representative and bounding of the work activities and conditions at M&C.

We agree that the choice of an RF is a TBD issue; however, since NIOSH cited a specific value in describing the welding scenario, SC&A believes it is appropriate to discuss it in the present context. The RF in question is specific to the welding scenario, which occurs for 4 h each month; it is not meant to be "representative and bounding of the work activities and conditions at M&C" that occupy the remainder of the month. As stated by SC&A (2019),

> we believe that the highly dispersive nature of the activities accompanying welding—grinding and wire brushing to achieve a clean surface—should be modeled using the highest reported RF in an indoor environment. According to [ORAUT (2012, table 3-1)], "vigorous sweeping by two workmen" resulted in RFs of $1.02 \times 10^{-2}$ to $4.2 \times 10^{-2}$.

We therefore maintain that an RF of $10^{-2}$ is more appropriate for this scenario.

**Observation 3: In estimating doses from the welding scenario, NIOSH should assign doses using the most claimant-favorable isotope of thorium or uranium, selected from isotopes known to have been used at M&C.**

NIOSH (2019b, p. 6) "agrees with this observation and intends to apply it to our exposure model." SC&A recommends that this observation be closed.

## References

Decisioneering, Inc. (2001). Crystal Ball 2000 (Version 2000.2) [Computer software and manual]. Denver, CO: Author.

Gilbert, R. O. (1987). *Statistical methods for environmental pollution monitoring*. New York: Van Nostrand Reinhold.

Helsel, D. R., & Cohn, T. A. (1988). Estimation of descriptive statistics for multiply censored water quality data. *Water Resources Research, 24,* 1997–2004.

Lee, L. (2020). *R Package NADA: Nondetects and data analysis for environmental data* (version 1.6-1.1) [Computer software and manual]. Retrieved from https://CRAN.R-project.org/package=NADA

National Institute for Occupational Safety and Health (NIOSH). (2019a). *Metals and Controls Corp. thorium and welding exposure model* [White paper]. Retrieved from SRDB Ref. ID 175938

National Institute for Occupational Safety and Health (NIOSH). (2019b). *SC&A review of Metals and Controls Corp. thorium and welding exposure model* [Response paper]. Retrieved from SRDB Ref. ID 178695

Oak Ridge Associated Universities Team (ORAUT). (2005). *Analysis of coworker bioassay data for internal dose assignment* (ORAUT-OTIB-0019, rev. 01). Retrieved from SRDB Ref. ID 19438

Oak Ridge Associated Universities Team (ORAUT). (2006). *Generating summary statistics for coworker bioassay data* (ORAUT-PROC-0095, rev. 00).

Oak Ridge Associated Universities Team (ORAUT). (2012). *Dose reconstruction during residual radioactivity periods at Atomic Weapons Employer facilities* (ORAUT-OTIB-0070, rev. 01). Retrieved from SRDB Ref. ID 108851

Oak Ridge Associated Universities Team (ORAUT). (2014). *Analysis of stratified coworker datasets* (ORAUT-RPRT-0053, rev. 02). Retrieved from https://www.cdc.gov/niosh/ocas/pdfs/orau/oraurpts/or-rprt-53-r2.pdf

Oak Ridge Associated Universities Team (ORAUT). (2019). *Review of SC&A's calculation of M&C Th232/U235 ratios*. Retrieved from SRDB Ref ID 178614

Roy F. Weston, Inc. (Weston). (1996). *Texas Instruments Incorporated, Attleboro Facility: Building interiors remediation drainage system characterization*. Retrieved from SRDB Ref. ID 165965

SC&A, Inc. (2012). *Review of new surrogate data for estimating intakes of uranium at General Steel Industries* [Draft white paper]. Retrieved from https://www.cdc.gov/niosh/ocas/pdfs/abrwh/scarpts/sca-gsinewsd-r0.pdf

SC&A, Inc. (2019). *Review of NIOSH's "Metals and Controls Corp. thorium and welding exposure model"* [Memorandum from Robert Anigstein to Work Group on Metals and Controls Corp.]. Retrieved from SRDB Ref. ID 177001

Sowell, L. L. (1985). *Radiological survey of the Texas Instruments site, Attleboro, Massachusetts*. Retrieved from SRDB Ref. ID 94371