Draft

SC&A Technical Response to NIOSH Regarding Data Completeness of Proposed In-Vivo Thorium Coworker Model for Fernald

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ABBREVIATIONS AND ACRONYMS

CI	confidence interval
µg	microgram
MDA	minimum detectable activity
mg	milligrams
MIVRML	Mobile In-Vivo Radiation Monitoring Laboratory
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health
SC&A	S. Cohen and Associates (SC&A, Inc.)

1.0 INTRODUCTION

In June of 2010, SC&A transmitted its review (SC&A 2010) of the proposed National Institute for Occupational Safety and Health (NIOSH) thorium coworker model for the period of 1968–1989 (NIOSH 2008). This technical response presents additional analyses relevant to the SC&A 2010 review prompted by subsequent work group discussions on some of the key issues, as described below. It is important to note that while the NIOSH coworker model spans the period from 1968–1989, the main subject of these additional analyses is the in-vivo data given in milligrams (mg) of Th for the operational thorium period from 1968–1979.[1] After 1979, there were no known thorium processing campaigns, so thorium exposure potential would be related to the storage, handling, and repackaging of thorium materials, as Fernald became the national repository for thorium beginning in 1972. Potential thorium exposures incurred in the "post-operational" thorium period (1980–1989) are discussed in SC&A 2010, Section 3.3, and elsewhere in that report.

On February 3, 2011, NIOSH posted responses to a number of the findings identified in SC&A 2010 (NIOSH 2011). The issues relating to the completeness of thorium monitoring coverage were discussed briefly at the February 9, 2011, work group meeting, and more thoroughly at the April 19, 2011, work group meeting. This addendum presents an additional analysis that pertains to two of the major discussion points that arose from NIOSH's initial response and were discussed in the work group meetings. The two issues in question can be summarized as follows:

(1) Aside from 1968, thorium workers cannot be adequately identified in the in-vivo records. Therefore, it is unknown whether their exposure potential was sufficiently monitored or can be reasonably bounded by monitoring data for non-thorium worker job types.

(2) Evidence suggests that thorium workers were not targeted directly for in-vivo monitoring; however, it has been suggested that workers with the higher exposure potential (and therefore higher in-vivo results) were targeted more frequently for monitoring. This would result in a correlation between the frequency of monitoring and the distribution of lung burdens, which should be evident in the data.

In relation to these issues, NIOSH stated the following in their February 3, 2011, response:

> *SRDB 38124* [**Redacted** 2007] *states that chemical operators were not selected for counting on the basis of if they did thorium work or not. All chemical operators were treated the same for selection. Selection was based on a routine schedule, or based on involvement with an event,* ***or due to previously high in-vivo counts****… measurements were not limited to those identified as 'thorium workers.' It would seem likely that, given some of the high in-vivo results came from other individuals, the site* ***was targeting individuals known to be performing rad work and who were likely to have intakes****.* [Emphasis added.]

[1] While the operational period extended until 1979, in-vivo data expressed in mg Th ended in 1978, so the analyses will focus on the available mg Th data.

Subsequent discussions during the February 9th work group[2] meeting further expanded on this response and concluded with the statement by NIOSH that thorium exposures can be bounded by the in-vivo results for chemical operators, because that category represents workers with the highest exposure potential. Furthermore, NIOSH asserted that the available monitoring data are sufficiently bounding, because chemical operators are not under-represented, and workers with higher potential for intakes were targeted more frequently.

During the April 19th work group meeting, SC&A presented additional analysis that compared the thorium lung burdens for identifiable thorium workers to those for the chemical operator group. These comparisons, along with some explanatory text, are presented in Section 3.1 of this report. The premise that workers with higher thorium exposures were targeted more frequently is analyzed in Section 2.0, which explores the correlation between the number of times a worker was sampled (sampling frequency) and the relative magnitude of their intake for both uranium and thorium. Attachment 1 expands upon the analysis presented in Section 2.0 and includes data outside the operational thorium period (post-1979).

2.0 SUMMARY OF FINDINGS:

Finding 1: When comparing the rank-ordered lung burdens for identifiable thorium workers to the monitoring records for chemical operators, the thorium worker in-vivo results were generally higher than chemical operators at almost all percentiles and, therefore, do not appear to be bounded by chemical operator lung burdens. In light of these perceived differences between the two subgroups in the rank-order analysis, a more robust analytical approach was adopted that compares the data on an annual basis. The results of this analysis show that the thorium subgroup 95th percentiles are higher in all but 4 years when compared with either the all workers or chemical operator 95th percentiles, and the means for the thorium samples are higher than the means for the other two groups in all but a few years. However, with the exception of 1971, no significant differences were found between the thorium subgroup, the chemical operators, and all worker categories when comparing the non-parametric 95% confidence intervals for the 95th percentiles of the three groups. (Please refer to Sections 3.1 and 3.2.) It is noteworthy that no evidence was found that the all worker or chemical operator groups provide a definitive upper bound for the thorium worker exposure.

Finding 2: Less than 3% of the in-vivo records for mg Th are at or above the assumed minimum detectable activity (MDA) of 6 mg. This, combined with uncertainties regarding the accuracy and veracity of the MDA, call the utility of the model into question. Nonetheless, thorium workers appear to be well represented among the in-vivo results at or above the MDA. Whereas thorium workers only comprise 7% of the total number of workers monitored, they make up over 20% of the workers who had positive results. Similarly, thorium worker samples comprise only 13% of the total samples, while they make up nearly 33% of the positive results identified.

Finding 3: When comparing a worker's monitoring frequency to the relative magnitude of their lung burden results, it was observed that thorium monitoring actually had a slight negative bias at the median and average lung burdens. **That is, there was no positive linear correlation**

[2] NOTE: The February 9, 2011, work group transcript is currently unavailable.

observed between the number of times a worker was monitored for thorium intake and the actual magnitude of their results. Conversely, uranium monitoring results showed a much better linear correlation between monitoring frequency and the relative magnitude of results. This strongly suggests that the in-vivo program may have been targeting higher risk workers based on uranium activities and not thorium projects. (Please refer to Section 4.0 and Attachment 1.)

3.0 SECTION 1: COMPARISON OF THE IN-VIVO RECORDS FOR IDENTIFIED THORIUM WORKERS VERSUS CHEMICAL OPERATORS

3.1 Analysis of Raw Data Unadjusted for the Stated MDA of 6 mg Th

As presented in the introduction, perhaps the most important facet of the thorium in-vivo coworker model is whether the most highly exposed workers are adequately represented in the database that underlies the thorium coworker model. Sections 3.1.1 and 3.1.2 of SC&A 2010 present analyses which suggest that the limited set of workers who could be identified as thorium workers had a significantly higher exposure potential than the entire worker population.

This finding was first discussed briefly during the February 2011 Fernald Work Group meeting, with the original response from NIOSH being that the dose to thorium workers is adequately bounded by the dose to chemical operators as a whole. That is, NIOSH contends that the chemical operator subgroup comprises the workers with the highest risk for thorium exposure. That premise had not been investigated in SC&A's original review (SC&A 2010); therefore, an additional analysis is presented in this section to address the comparison of thorium workers specifically to chemical operators.

As stated in SC&A 2010, there are difficulties in establishing who worked with thorium and during what periods for all years except 1968 (the first year of in-vivo monitoring). Just prior to 1968, a memo was produced by Bob Starkey (Starkey 1967) that listed thorium workers (51 in total) with the explicit purpose of having them counted when the Mobile In-Vivo Radiation Monitoring Laboratory (MIVRML) was available on site. Based on the available records, approximately 55% of the 51 identified workers were counted in 1968. The Starkey memo is a useful resource, as it directly ties lung burdens to workers who were identified with thorium at the time. The data for the thorium workers in 1968 were compared against the chemical operator lung burdens during that same year; these data are presented in Figure 1. It is important to note that chemical operators who were identified as thorium workers in 1968 were not included in the 'chemical operator' subgroup of Figure 1, as this would have resulted in double counting.[3]

As seen in Figure 1, the thorium worker lung burdens overlap with chemical operators at about the 15th, 75th, and 95th percentiles, but clearly exceed the chemical worker burdens from about

[3] The Starkey memo was used to assign job titles in instances where no job title was specified in the in-vivo records. In 1968, nearly 60% of the records had no job title specified, so it is likely that a significant portion of those records were also for chemical operators. Of the 79 samples identified for chemical operators in 1968, 49 (or 62%) were identified via the Starkey memo, so there is considerable overlap. The double-counting effect was less pronounced in subsequent years.

the 20th to the 67th percentiles. Also of note is that the three highest results in 1968 were all for thorium workers.

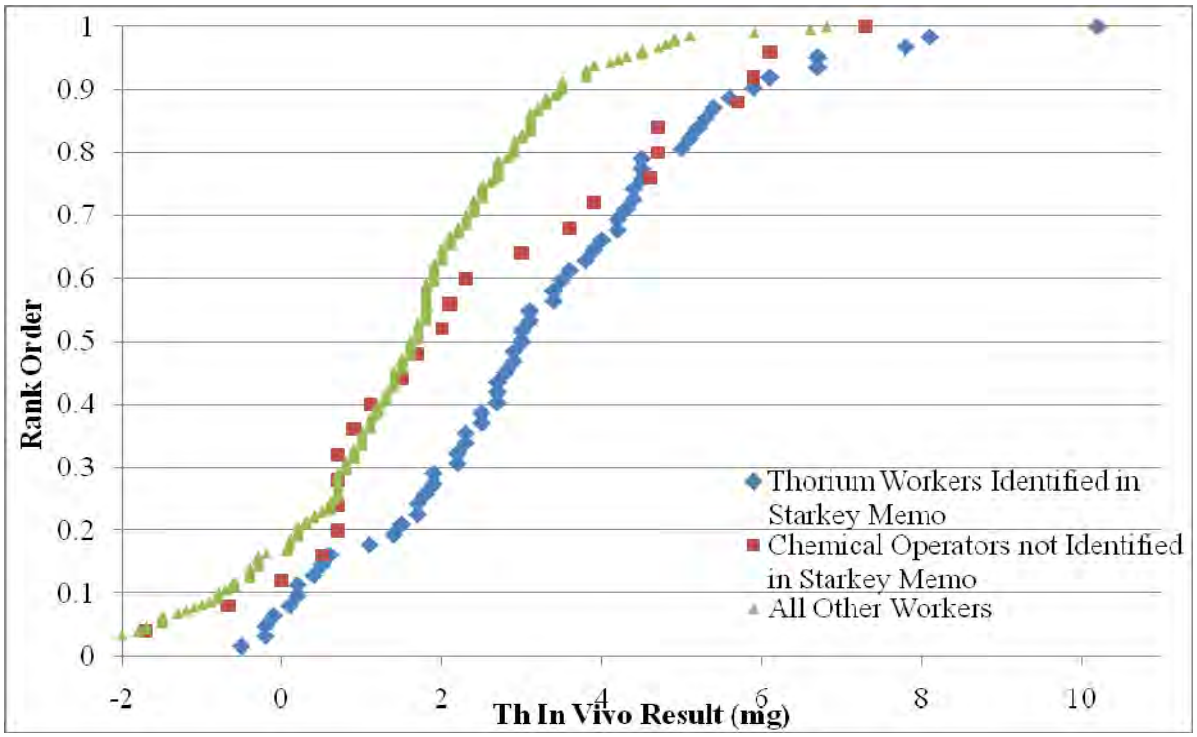

Figure 1. Comparison of In-Vivo Results (mg Th) for All Thorium Worker Job Titles versus Non-Thorium Chemical Operators in 1968

After 1968, it is very difficult to identify who worked with thorium and during which years; this makes it more difficult to compare the lung burdens for the thorium subgroup to chemical operators or other groups of workers. The only other resource that identifies thorium workers is the worker in-vivo log sheets, as outlined in Section 3.1.2 of SC&A 2010. However, there is no direct connection to suggest when, if at all, thorium was handled by these workers during the production period of interest (1968–1979).[4] For the purposes of comparison, SC&A assumed that every worker identified in the Starkey memo, as well as those identified as thorium workers on their individual log sheets (about 60 workers in total), handled thorium during their entire period of employment. This expanded subgroup of thorium workers is the subject of the remainder of this section, as well as the statistical analysis presented in Section 3.2. It is important to note that it is unlikely that any worker actually handled thorium during their entire period of employment, due to the intermittent processing of thorium at Fernald (Morris 2008). Thus, many of the thorium in-vivo measurements would actually be representative of uranium work instead of thorium work.

[4] As noted in the introduction, the period under consideration for in-vivo thorium monitoring extends from 1968 until 1989. However, thorium production at Fernald ceased in 1979; therefore, 1968–1979 is the period under consideration for this analysis. Analyses specifically for Th ceased in 1978; therefore, this analysis does not include data for 1979.

Based on the assumption of continuous thorium exposure during all periods of employment, the expanded thorium worker subgroup was compared to the chemical operators during the period of interest (1968–1979); the results are presented in Figure 2. **As shown in Figure 2, the expanded thorium worker subgroup appears to bound the chemical operator subgroup for almost all percentiles.** Interestingly, Figure 2 also shows that chemical operators who were never identified with thorium work (either through the Starkey memo or the individual log sheets) have a slightly lower exposure potential than the chemical operator group as a whole.

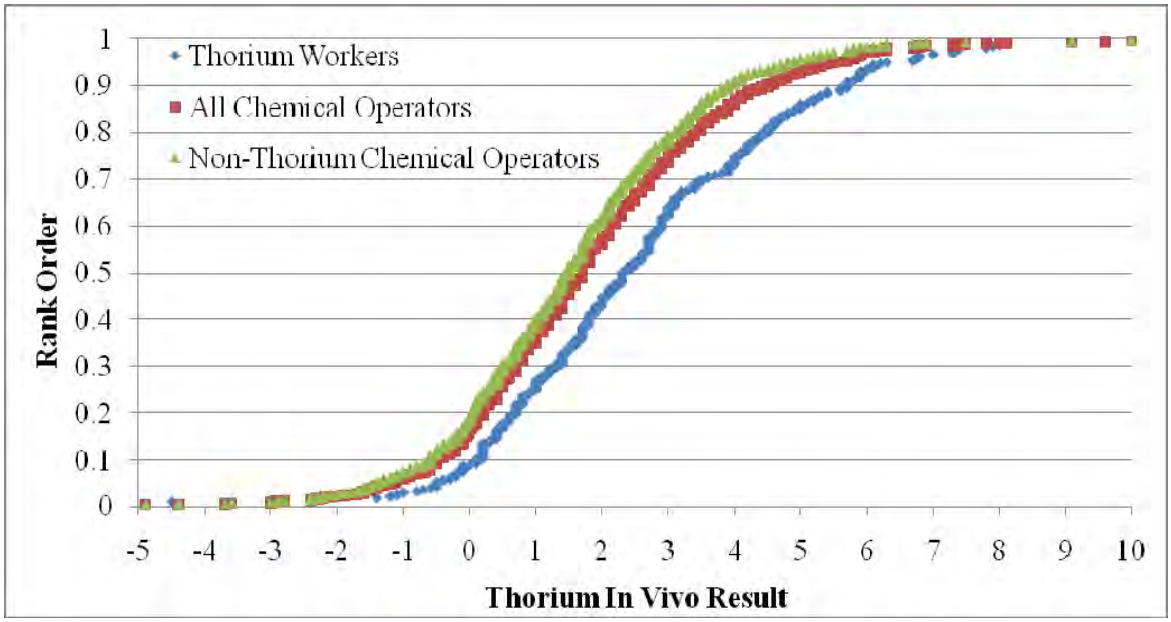

Figure 2. Rank-Ordered Comparison of In-Vivo Results (mg Th) for Thorium Workers and Chemical Operators (1968–1979)

Finally, Figure 3 compares the rank-ordered lung burdens for all chemical operators to those of all the workers monitored for thorium during the operational period. As the figure shows, the rank-ordered lung burdens for chemical operators are indistinguishable from the distribution for all workers. This strongly suggests the chemical operator subgroup does not bound doses for all workers.

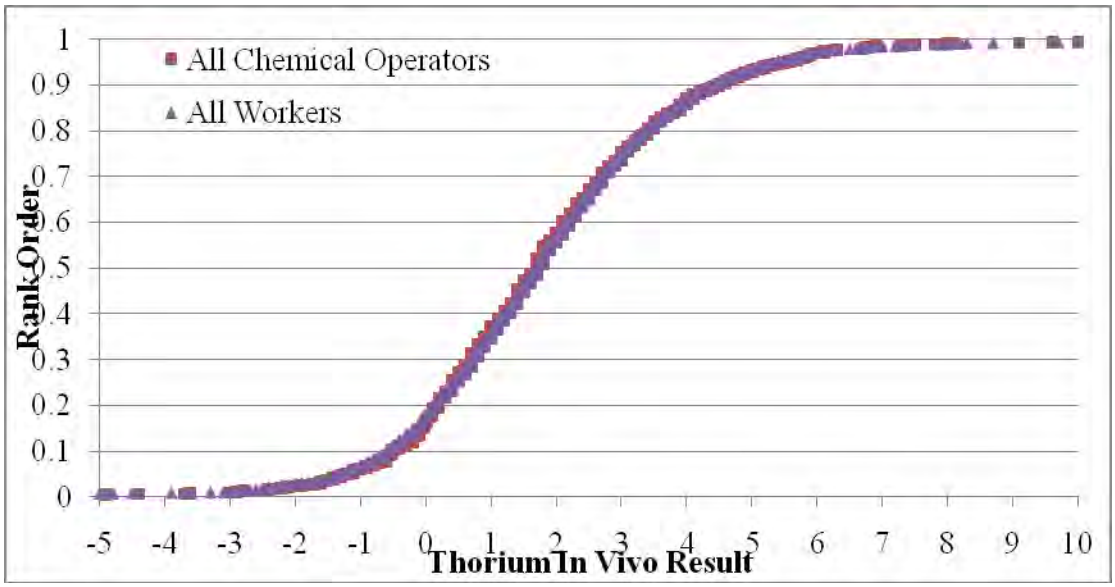

Figure 3. Rank-Ordered Comparison of In-Vivo Results (mg Th) for Chemical Operators and All Monitored Workers (1968–1979)

3.2 Additional Analysis of Worker Subgroup Data

To better understand the potential differences in thorium lung burden distributions in the subgroups of interest, additional statistical analyses beyond simple rank-ordered comparisons were performed. The subgroup of thorium workers analyzed in this section assumes that all workers identified in the 1968 Starkey memo and also by their in-vivo logbooks worked with thorium during the entire production period. Also note that in this analysis, chemical operators and thorium workers are not mutually exclusive; that is, there is some overlap between the two groups of workers. Table 1 shows selected statistics describing the distribution of thorium in-vivo test results in 1968 for all workers and for three subgroups of workers—thorium workers, chemical operators, and non-thorium chemical operators. Tables 2 through 11 contain similar information for the years 1969 through 1978, respectively.

In Table 1, the sample size in 1968 of 289 for all workers includes 75 samples for workers identified as thorium workers and 79 as chemical operators. Of the 79 chemical operator samples, all but 15 were also identified as thorium workers. The statistics reported for each group include the arithmetic mean, with the upper and lower bounds of the 95% confidence interval for the estimated mean, and the standard error of the mean. The spread of the distribution of test results is measured by the next eight statistics: the variance, the standard deviation and the coefficient of variation; the 5^{th}, 25^{th}, 50^{th}, 75^{th} and 95^{th} percentiles of the distribution of test results. Due to the wide variety of distributions encountered in the 4 groups over the 11-year period, nonparametric estimates of the upper and lower 95% confidence bounds (highlighted) for the 95^{th} percentile are shown in the table. **Examination of the nonparametric confidence bands for the 95^{th} percentile shows that most of the estimates of the 95^{th} percentile for the four groups of workers do not differ significantly.** Summary statistics for the distribution of test results are shown at the bottom of Tables 1 through 11, including the

maximum and minimum sample values, and the skew and kurtosis of the distribution. Note that the skew and kurtosis are 0 for a normal distribution.

The estimates of the 95th percentile and the nonparametric 95% confidence interval for the 95th percentile are summarized for 1968 through 1978 for the four groups of workers in Table 12. Examination of the 95th percentile values in Table 12 shows that the 95th percentile of the thorium worker samples exceeds the 95th percentile for all workers and for all chemical operators in 7 of the 11 years. However, examination of the nonparametric confidence bands for the 95th percentile shows that the only significant difference between these two groups occurs in 1971.

Figure 4 shows time series plots of the 95th percentiles for the four groups of workers in Table 12. The 95th percentile of the distribution for chemical operators tracks closely with the all worker distribution over the entire period. The 95th percentiles for all four groups are very similar from 1972 on. Prior to 1972, the following differences are observed:

- In 1968, the 95th percentile for thorium workers is approximately the same as for chemical operators and higher than for all workers.
- In 1969, the 95th percentile for thorium workers is below that for chemical operators and all workers.
- The ordering is reversed in 1970 and 1971, with the 95th percentile for thorium workers exceeding the other two groups.

Based on the confidence intervals shown in Table 12, 1971 is the only year with a significant difference between the thorium workers and all workers 95th percentiles. Viewed from the claimant perspective, however, there is no year when the all worker 95th percentile or the chemical operator 95th percentile is significantly higher than the 95th percentile for the thorium workers. Hence, there is no evidence that either of these two groups provides a definitive upper bound for the upper end of thorium worker exposures. The 95th percentile for non-thorium chemical operators is lower than the other three groups prior to 1973.

In Table 1, the mean values for two groups in 1968 appear to differ significantly from the other two, since the lower bounds of the confidence intervals (CIs) for the mean for the thorium and chemical operators exceed the upper bounds of the confidence intervals for the all worker and non-thorium chemical operator subgroups. This apparent difference in mean values is suspect, however, since the groups are non-exclusive. The means of the four groups of workers are plotted for the years 1968 through 1978 in Figure 5. The apparently significant difference between the all worker group and the thorium and chemical operator group only occurs in 1968. In 1969, the means are very close. From 1970 to 1972 and in 1978, the mean value for the thorium workers is somewhat higher than the means for the other groups.

The estimates of the mean thorium in-vivo test result and the 95% confidence interval for the mean are summarized for 1968 through 1978 for the four groups of workers in Table 13. Examination of the mean values in Table 13 shows that the mean of the thorium worker samples exceeds the mean for all workers in all but one year (1975), and the mean of the thorium worker samples exceeds the mean for the all chemical operator group in 8 of the 11 years. The

confidence intervals indicate the thorium worker mean value is significantly higher than the all worker mean in 1968, and the difference may have borderline significance in 1970, 1971, and 1972. The mean for the thorium workers does not appear to be significantly higher in later years. On the other hand, there is no year when the all worker mean or the chemical operator mean is significantly higher than the thorium worker mean. This brings into question whether either of these two groups provides a plausible upper bound for the thorium worker exposures.

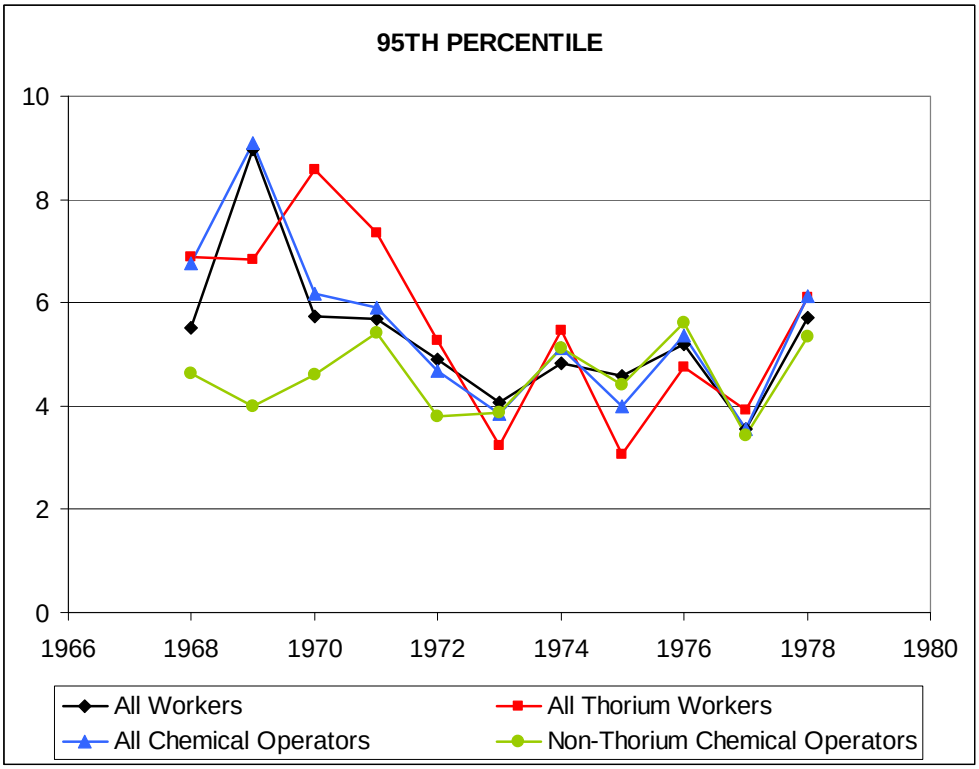

Figure 4. Time Series Plot of the 95th Percentile of the Thorium Test Results for Four Groups of Workers, 1968–1978

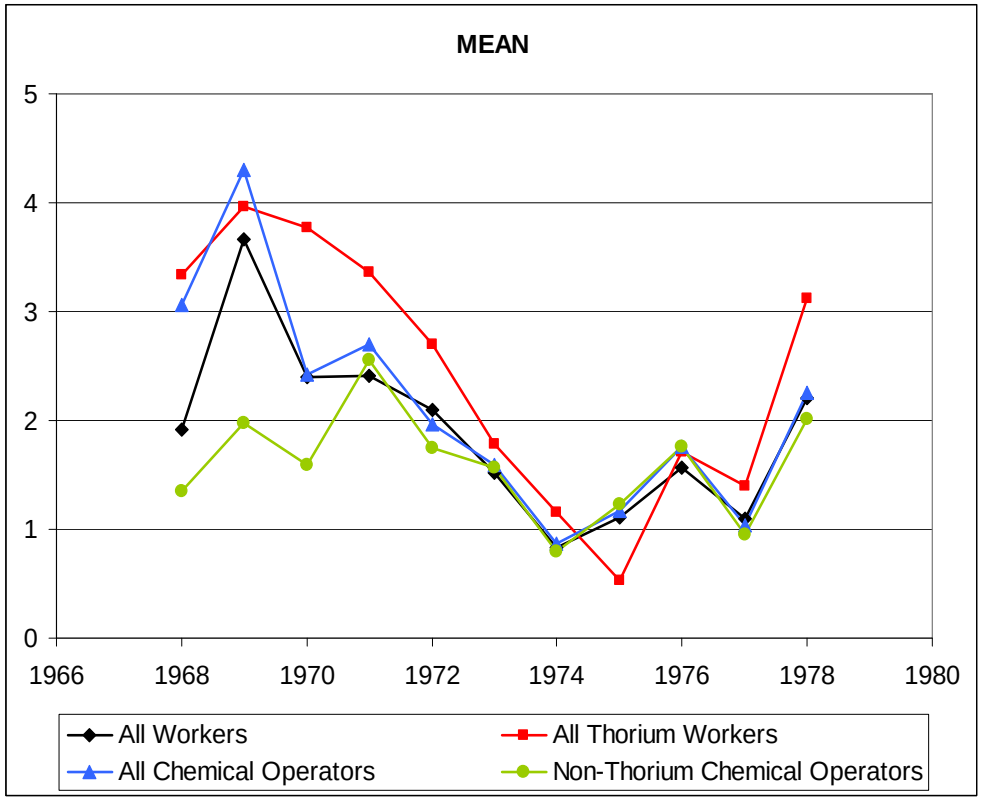

Figure 5. Time Series Plot of the Mean Thorium In-Vivo Test Results for Four Groups of Workers, 1968–1978

Table 1. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1968

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	289	75	79	15
Upper Bound of 95% CI for Mean	2.2	3.8	3.6	2.3
Mean	1.9	3.3	3.1	1.4
Lower Bound of 95% CI for Mean	1.7	2.8	2.5	0.4
Standard Error of Mean	0.13	0.25	0.26	0.48
Variance	4.6	4.7	5.4	3.4
Standard Deviation	2.1	2.2	2.3	1.8
Coefficient of Variation	1.1	0.6	0.8	1.4
5^{th} Percentile	-1.3	0.0	-0.1	-1.0
25^{th} Percentile	0.7	1.9	1.3	0.6
Median	1.8	3.0	3.0	0.7
75^{th} Percentile	3.1	4.6	4.6	2.3
Lower Bound of 95% CI for 95^{th} Percentile	4.8	5.9	5.9	3.0
95^{th} Percentile	5.5	6.9	6.8	4.6
Upper Bound of 95% CI for 95^{th} Percentile	6.6	10.2	10.2	4.7
Maximum	10.2	10.2	10.2	4.7
Minimum	-8.8	-0.5	-1.7	-1.7
Range	19.0	10.7	11.9	6.4
Skew	-0.14	0.51	0.46	0.61
Kurtosis	3.15	0.35	0.06	-0.17

Note that the results for 1968 presented here will differ from the analysis presented in Figure 1 of Section 3.1 because Figure 1 only analyzed the thorium workers identified in the Starkey memo while this section analyzes the 'expanded group' of thorium workers which includes those identified in their logbooks.

Table 2. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1969

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	87	24	11	4
Upper Bound of 95% CI for Mean	4.6	5.0	6.3	3.9
Mean	3.7	4.0	4.3	2.0
Lower Bound of 95% CI for Mean	2.7	2.9	2.3	0.1
Standard Error of Mean	0.49	0.54	1.00	0.96
Variance	21.1	7.1	11.0	3.7
Standard Deviation	4.6	2.7	3.3	1.9
Coefficient of Variation	1.3	0.7	0.8	1.0
5^{th} Percentile	0.0	0.4	0.5	0.0
25^{th} Percentile	0.9	1.8	2.3	0.8
Median	2.7	4.3	4.4	2.0
75^{th} Percentile	4.7	5.6	5.3	3.2
Lower Bound of 95% CI for 95^{th} Percentile	7.0	5.7	5.7	1.1
95^{th} Percentile	9.0	6.8	9.1	4.0
Upper Bound of 95% CI for 95^{th} Percentile	32.5	12.4	12.4	4.2
Maximum	32.5	12.4	12.4	4.2
Minimum	-0.9	0.2	-0.2	-0.2
Range	33.4	12.2	12.6	4.4
Skew	3.69	1.16	1.32	0.06
Kurtosis	19.18	3.03	3.27	-1.89

Table 3. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1970

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	155	18	27	20
Upper Bound of 95% CI for Mean	2.7	5.0	3.2	2.3
Mean	2.4	3.8	2.4	1.6
Lower Bound of 95% CI for Mean	2.1	2.5	1.6	0.9
Standard Error of Mean	0.16	0.65	0.42	0.35
Variance	3.9	7.6	4.7	2.4
Standard Deviation	2.0	2.8	2.2	1.5
Coefficient of Variation	0.8	0.7	0.9	1.0
5^{th} Percentile	-0.3	0.5	-0.1	-0.2
25^{th} Percentile	1.0	2.8	1.1	0.4
Median	2.1	3.1	1.7	1.4
75^{th} Percentile	3.7	3.9	3.8	2.2
Lower Bound of 95% CI for 95^{th} Percentile	4.8	5.9	4.6	2.8
95^{th} Percentile	5.7	8.6	6.2	4.6
Upper Bound of 95% CI for 95^{th} Percentile	7.5	11.8	8.0	4.8
Maximum	11.8	11.8	8.0	4.8
Minimum	-1.5	0.4	-0.5	-0.5
Range	13.3	11.4	8.5	5.3
Skew	1.00	1.66	0.87	0.88
Kurtosis	2.54	3.45	0.29	0.14

Table 4. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1971

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	583	52	178	136
Upper Bound of 95% CI for Mean	2.6	4.0	3.0	2.9
Mean	2.4	3.4	2.7	2.6
Lower Bound of 95% CI for Mean	2.3	2.7	2.4	2.2
Standard Error of Mean	0.08	0.34	0.15	0.16
Variance	3.7	6.0	3.9	3.4
Standard Deviation	1.9	2.4	2.0	1.8
Coefficient of Variation	0.8	0.7	0.7	0.7
5^{th} Percentile	-0.3	-0.1	-0.1	-0.1
25^{th} Percentile	1.1	1.5	1.4	1.4
Median	2.3	3.0	2.6	2.5
75^{th} Percentile	3.5	5.1	3.8	3.5
Lower Bound of 95% CI for 95^{th} Percentile	5.3	6.8	5.3	5.0
95^{th} Percentile	5.7	7.3	5.9	5.4
Upper Bound of 95% CI for 95^{th} Percentile	6.3	9.6	7.4	10.0
Maximum	11.6	9.6	10.0	10.0
Minimum	-2.5	-0.5	-1.9	-1.9
Range	14.1	10.1	11.9	11.9
Skew	0.80	0.42	0.85	0.88
Kurtosis	1.74	-0.54	1.75	2.64

Table 5. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1972

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	239	34	122	92
Upper Bound of 95% CI for Mean	2.3	3.3	2.3	2.1
Mean	2.1	2.7	2.0	1.7
Lower Bound of 95% CI for Mean	1.9	2.2	1.7	1.4
Standard Error of Mean	0.11	0.28	0.15	0.17
Variance	2.8	2.7	2.9	2.8
Standard Deviation	1.7	1.6	1.7	1.7
Coefficient of Variation	0.8	0.6	0.9	1.0
5^{th} Percentile	-0.5	0.6	-0.5	-0.6
25^{th} Percentile	0.8	1.5	0.7	0.4
Median	2.0	2.1	1.9	1.8
75^{th} Percentile	3.3	4.1	3.2	2.8
Lower Bound of 95% CI for 95^{th} Percentile	4.5	4.5	4.1	3.6
95^{th} Percentile	4.9	5.3	4.7	3.8
Upper Bound of 95% CI for 95^{th} Percentile	5.3	5.9	5.9	9.1
Maximum	9.1	5.9	9.1	9.1
Minimum	-3.0	0.2	-3.0	-3.0
Range	12.1	5.7	12.1	12.1
Skew	0.36	0.34	0.60	0.70
Kurtosis	0.58	-1.12	1.78	3.23

Table 6. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1973

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	205	28	106	83
Upper Bound of 95% CI for Mean	1.8	2.2	1.9	1.9
Mean	1.5	1.8	1.6	1.6
Lower Bound of 95% CI for Mean	1.3	1.4	1.3	1.2
Standard Error of Mean	0.13	0.22	0.15	0.17
Variance	3.3	1.3	2.3	2.5
Standard Deviation	1.8	1.1	1.5	1.6
Coefficient of Variation	1.2	0.6	1.0	1.0
5^{th} Percentile	-1.5	0.1	-1.3	-1.4
25^{th} Percentile	0.5	0.8	0.7	0.7
Median	1.6	2.0	1.7	1.7
75^{th} Percentile	2.7	2.7	2.8	2.7
Lower Bound of 95% CI for 95^{th} Percentile	3.6	2.9	3.3	3.3
95^{th} Percentile	4.1	3.2	3.9	3.9
Upper Bound of 95% CI for 95^{th} Percentile	4.9	4.2	5.0	5.0
Maximum	11.7	4.2	5.0	5.0
Minimum	-2.8	-0.2	-2.4	-2.4
Range	14.5	4.4	7.4	7.4
Skew	0.65	0.04	-0.34	-0.38
Kurtosis	4.13	-0.93	-0.11	-0.19

Table 7. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1974

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	279	27	128	108
Upper Bound of 95% CI for Mean	1.2	2.4	1.3	1.3
Mean	0.8	1.2	0.9	0.8
Lower Bound of 95% CI for Mean	0.5	-0.1	0.4	0.3
Standard Error of Mean	0.19	0.64	0.23	0.25
Variance	9.7	11.0	6.9	6.6
Standard Deviation	3.1	3.3	2.6	2.6
Coefficient of Variation	3.8	2.9	3.0	3.2
5th Percentile	-3.2	-6.3	-2.9	-2.9
25th Percentile	-0.5	0.1	-0.1	-0.1
Median	1.1	1.7	1.0	1.0
75th Percentile	2.5	2.9	2.3	2.0
Lower Bound of 95% CI for 95th Percentile	4.4	4.1	3.6	3.5
95th Percentile	4.8	5.5	5.1	5.1
Upper Bound of 95% CI for 95th Percentile	5.8	5.9	5.9	6.0
Maximum	18.0	5.9	6.0	6.0
Minimum	-16.0	-8.1	-11.9	-11.9
Range	34.0	14.0	17.9	17.9
Skew	-0.88	-1.42	-1.41	-1.42
Kurtosis	8.08	2.72	5.61	6.43

Table 8. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1975

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	233	23	111	92
Upper Bound of 95% CI for Mean	1.4	1.3	1.6	1.7
Mean	1.1	0.5	1.2	1.2
Lower Bound of 95% CI for Mean	0.8	-0.3	0.7	0.7
Standard Error of Mean	0.15	0.41	0.21	0.25
Variance	5.4	3.9	5.1	5.5
Standard Deviation	2.3	2.0	2.3	2.4
Coefficient of Variation	2.1	3.7	1.9	1.9
5th Percentile	-2.2	-2.6	-1.5	-1.5
25th Percentile	-0.2	-0.5	0.0	0.0
Median	1.0	0.4	1.4	1.5
75th Percentile	2.5	2.0	2.6	2.5
Lower Bound of 95% CI for 95th Percentile	4.0	2.6	3.5	3.6
95th Percentile	4.6	3.1	4.0	4.4
Upper Bound of 95% CI for 95th Percentile	5.8	4.0	6.3	6.9
Maximum	8.3	4.0	6.9	6.9
Minimum	-10.0	-4.5	-10.0	-10.0
Range	18.3	8.5	16.9	16.9
Skew	-0.39	-0.56	-1.00	-1.10
Kurtosis	2.81	0.76	5.13	5.34

Table 9. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1976

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	215	24	114	93
Upper Bound of 95% CI for Mean	1.9	2.4	2.4	2.5
Mean	1.6	1.7	1.8	1.8
Lower Bound of 95% CI for Mean	1.2	1.0	1.2	1.0
Standard Error of Mean	0.18	0.34	0.31	0.37
Variance	7.3	2.8	10.7	12.5
Standard Deviation	2.7	1.7	3.3	3.5
Coefficient of Variation	1.7	1.0	1.9	2.0
5^{th} Percentile	-1.5	-0.6	-1.2	-1.4
25^{th} Percentile	0.2	0.4	0.2	0.0
Median	1.3	1.5	1.1	1.0
75^{th} Percentile	2.6	2.8	2.9	2.8
Lower Bound of 95% CI for 95^{th} Percentile	4.4	3.5	4.9	4.9
95^{th} Percentile	5.2	4.8	5.6	6.0
Upper Bound of 95% CI for 95^{th} Percentile	6.2	5.2	25.0	-2.4
Maximum	25.0	5.2	25.0	25.0
Minimum	-2.8	-1.1	-2.4	-2.4
Range	27.8	6.3	27.4	27.4
Skew	3.95	0.54	4.15	4.03
Kurtosis	29.73	-0.36	25.40	22.76

Table 10. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1977

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	188	29	97	73
Upper Bound of 95% CI for Mean	1.3	1.9	1.3	1.3
Mean	1.1	1.4	1.0	0.9
Lower Bound of 95% CI for Mean	0.9	0.9	0.7	0.6
Standard Error of Mean	0.11	0.26	0.14	0.16
Variance	2.1	1.9	2.0	2.0
Standard Deviation	1.5	1.4	1.4	1.4
Coefficient of Variation	1.3	1.0	1.4	1.5
5^{th} Percentile	-1.0	-0.5	-0.9	-1.0
25^{th} Percentile	-0.1	0.6	-0.1	-0.1
Median	1.0	1.3	1.0	0.9
75^{th} Percentile	2.0	2.0	1.8	1.8
Lower Bound of 95% CI for 95^{th} Percentile	3.2	2.9	2.9	2.7
95^{th} Percentile	3.6	3.9	3.6	3.4
Upper Bound of 95% CI for 95^{th} Percentile	4.5	4.8	4.8	4.5
Maximum	5.3	4.8	4.8	4.5
Minimum	-2.6	-1.4	-2.4	-2.4
Range	7.9	6.2	7.2	6.9
Skew	0.29	0.49	0.41	0.32
Kurtosis	0.06	0.59	0.03	-0.20

Table 11. Statistics for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1978

Statistic	All Workers	All Thorium Workers	All Chemical Operators	Non-Thorium Chemical Operators
Number of Samples	144	18	70	53
Upper Bound of 95% CI for Mean	2.5	4.1	2.7	2.6
Mean	2.2	3.1	2.2	2.0
Lower Bound of 95% CI for Mean	1.9	2.1	1.8	1.5
Standard Error of Mean	0.17	0.51	0.24	0.27
Variance	4.0	4.7	4.2	3.9
Standard Deviation	2.0	2.2	2.0	2.0
Coefficient of Variation	0.9	0.7	0.9	1.0
5^{th} Percentile	-0.7	0.2	-0.9	-1.1
25^{th} Percentile	0.8	1.5	0.9	0.9
Median	2.0	3.0	2.1	1.9
75^{th} Percentile	3.7	4.5	3.4	3.3
Lower Bound of 95% CI for 95^{th} Percentile	5.0	5.7	4.4	4.1
95^{th} Percentile	5.7	6.1	6.1	5.3
Upper Bound of 95% CI for 95^{th} Percentile	6.9	7.3	7.5	7.5
Maximum	7.5	7.3	7.5	7.5
Minimum	-2.2	0.1	-2.2	-2.2
Range	9.7	7.2	9.7	9.7
Skew	0.32	0.25	0.43	0.44
Kurtosis	-0.22	-0.83	0.25	0.65

Table 12. 95th Percentile of Thorium In-Vivo Test Results with 95% Confidence Interval for the 95th Percentile for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1968 to 1978

(Note: Values above the assumed MDA of 6 mg Th are highlighted.)

Year	All Workers			All Thorium Workers			All Chemical Operators			Non-Thorium Chemical Operators		
	Lower Bound of 95% CI for 95th Percentile	95th Percentile	Upper Bound of 95% CI for 95th Percentile	Lower Bound of 95% CI for 95th Percentile	95th Percentile	Upper Bound of 95% CI for 95th Percentile	Lower Bound of 95% CI for 95th Percentile	95th Percentile	Upper Bound of 95% CI for 95th Percentile	Lower Bound of 95% CI for 95th Percentile	95th Percentile	Upper Bound of 95% CI for 95th Percentile
1968	4.8	5.5	6.6	5.9	6.9	10.2	5.9	6.8	10.2	3.0	4.6	4.7
1969	7.0	9.0	32.5	5.7	6.8	12.4	5.7	9.1	12.4	1.1	4.0	4.2
1970	4.8	5.7	7.5	5.9	8.6	11.8	4.6	6.2	8.0	2.8	4.6	4.8
1971	5.3	5.7	6.3	6.8	7.3	9.6	5.3	5.9	7.4	5.0	5.4	10.0
1972	4.5	4.9	5.3	4.5	5.3	5.9	4.1	4.7	5.9	3.6	3.8	9.1
1973	3.6	4.1	4.9	2.9	3.2	4.2	3.3	3.9	5.0	3.3	3.9	5.0
1974	4.4	4.8	5.8	4.1	5.5	5.9	3.6	5.1	5.9	3.5	5.1	6.0
1975	4.0	4.6	5.8	2.6	3.1	4.0	3.5	4.0	6.3	3.6	4.4	6.9
1976	4.3	5.2	5.8	3.5	4.8	5.2	4.7	5.4	17.0	4.7	5.6	25.0
1977	3.2	3.6	4.5	2.9	3.9	4.8	2.9	3.6	4.8	2.7	3.4	4.5
1978	5.0	5.7	6.9	5.7	6.1	7.3	4.4	6.1	7.5	4.1	5.3	7.5

Table 13. Mean Thorium In-Vivo Test Results of 95% Confidence Interval for the Mean for All Workers, Thorium Workers, Chemical Operators, and Non-Thorium Chemical Operators, 1968 to 1978

Year	All Workers			All Thorium Workers			All Chemical Operators			Non-Thorium Chemical Operators		
	Lower Bound of 95% CI for Mean	Mean	Upper Bound of 95% CI for Mean	Lower Bound of 95% CI for Mean	Mean	Upper Bound of 95% CI for Mean	Lower Bound of 95% CI for Mean	Mean	Upper Bound of 95% CI for Mean	Lower Bound of 95% CI for Mean	Mean	Upper Bound of 95% CI for Mean
1968	1.7	1.9	2.2	2.8	3.3	3.8	2.5	3.1	3.6	0.4	1.4	2.3
1969	2.7	3.7	4.6	2.9	4.0	5.0	2.3	4.3	6.3	0.1	2.0	3.9
1970	2.1	2.4	2.7	2.5	3.8	5.0	1.6	2.4	3.2	0.9	1.6	2.3
1971	2.3	2.4	2.6	2.7	3.4	4.0	2.4	2.7	3.0	2.2	2.6	2.9
1972	1.9	2.1	2.3	2.2	2.7	3.3	1.7	2.0	2.3	1.4	1.7	2.1
1973	1.3	1.5	1.8	1.4	1.8	2.2	1.3	1.6	1.9	1.2	1.6	1.9
1974	0.5	0.8	1.2	-0.1	1.2	2.4	0.4	0.9	1.3	0.3	0.8	1.3
1975	0.8	1.1	1.4	-0.3	0.5	1.3	0.7	1.2	1.6	0.7	1.2	1.7
1976	1.2	1.6	1.9	1.0	1.7	2.4	1.2	1.8	2.4	1.0	1.8	2.5
1977	0.9	1.1	1.3	0.9	1.4	1.9	0.7	1.0	1.3	0.6	0.9	1.3
1978	1.9	2.2	2.5	2.1	3.1	4.1	1.8	2.2	2.7	1.5	2.0	2.6

3.3 Analysis of Positive Thorium In-Vivo Results at or Above 6 mg Thorium

For the comparisons in Sections 3.1 and 3.2, the veracity and utility of the underlying data were not questioned. This section provides an overview of the monitoring records that were at or above the stated MDA of 6 mg. Overall, there were 2,667 thorium measurements performed from 1968 through 1978, with only 76 (<3%) of those measurements at or above the assumed MDA of 6 mg. Table 14 provides a summary of the available positive records and how they are distributed between the groups of interest. Chemical operators had more positive results than thorium workers by a factor of about 1.25; however, chemical operators had more than 3 times the number of total samples when compared to thorium workers. Approximately 7% of the samples taken for thorium workers were at or above the assumed MDA, while about 3% of those for chemical operators were above the MDA (this is slightly higher than the percentage for all workers, at 2.8%).

The median results for all three worker groups are very close in magnitude, with thorium workers slightly higher at 7 mg Th. Thorium workers have the lowest average positive result, which is likely due to the fact that the maximum result for this worker subgroup was less than half that of chemical operators. The very highest result (32.5 mg Th) was for a worker whose job title is unknown, but whose plant was designated as "QA or QC." Curiously, over 1/3 (~35.5%) of the positive samples were identified with Plant 5, which had no known thorium production campaigns.

Table 14. Overview of Positive Th Results

Worker Category	# Workers with Positive Results	# Positive Samples	% of Total Samples	Average Result (mg)	Median Result (mg)	Maximum Result (mg)
Thorium Workers[1]	12	25	7.1%	7.55	7	12.4
Chemical Operators[2]	21	33	3.1%	8.24	6.8	25
All Workers[3]	57	76	2.8%	8.51	6.95	32.5

[1] Includes one worker who had measurements on consecutive days; otherwise, there were at least 4 months between samples

[2] All workers had at least 4 months between samples

[3] Includes one worker who had measurements 1 month apart; otherwise, there were at least 4 months between samples

Thorium workers appear to be well represented when examining the in-vivo results at or above the assumed MDA of 6 mg Th. Thorium workers comprised over 20% of the workers who had positive results and nearly 1/3 of all positive samples. By comparison, thorium workers comprised ~7% of the total number of monitored workers and ~13% of the total samples for Th.

4.0 SECTION 2: CORRELATION BETWEEN SAMPLING FREQUENCY AND MAGNITUDE OF LUNG BURDEN FOR IN-VIVO URANIUM AND THORIUM DURING MAJORITY OF THORIUM PRODUCTION PERIOD

The second issue discussed in this report regards the premise that workers were selected for monitoring frequency based on their exposure potential. According to this premise, the highest exposed workers are adequately represented by the available data, and any derived coworker model would be biased towards higher exposures. To examine this premise, SC&A compared the number of times a particular worker was sampled to the relative magnitude of their calculated lung burden (average, median, and maximum in-vivo results). If the frequency of monitoring was biased towards the higher exposed individuals, then one would expect a positive linear correlation between the two variables. The results of this comparison for uranium (U and U-235) and thorium (Th) are summarized in Table 15. Figures 6 through 8 plot the median in-vivo count results versus the sampling frequencies for the sampling types presented in Table 15. As in Section 1.0, only the period of known thorium production and thorium sampling was examined (1968–1978). It is important to note that for this analysis, all negative values were assumed to be 'non-detects' and converted to zero to avoid biasing the results. In-vivo results that were positive but less than the assumed MDA of 6 mg were assumed to represent real positive results.

Table 15. Excel Calculated Linear Trend Line Formulas and Correlation Coefficients for Uranium and Thorium Data during Periods of Thorium Production

Measured Radionuclide	Linear Trend Line Formula and Correlation Coefficients		
	Average	Median	Maximum
U-235	y = 0.0626x + 1.525 R^2 = 0.1469	y = 0.0535x + 2.0219 R^2 = 0.1133	y = 0.0531x + 0.4556 R^2 = 0.3895
U**	y = 0.0009x + 4.4191 R^2 = 0.0001	y = 0.1665x + 3.0844 R^2 = 0.05	y = 0.1456x + 2.3789 R^2 = 0.2037
Th	y = -0.0475x + 4.1759 R^2 = 0.0003	y = -0.1657x + 4.402 R^2 = 0.0041	y = 0.6643x + 1.8825 R^2 = 0.1375

* U-235 in-vivo samples may indicate monitoring for enriched uranium

** It is not known what was specifically being measured for the results labeled as 'U;' however, that is outside the scope of this report and not relevant to the analysis

As seen in Table 15, the average and median thorium results actually show a slight negative linear bias, which does not indicate that the job categories with high exposure potential to thorium were counted more frequently. The correlation between the maximum thorium in-vivo counting results and the frequency of monitoring showed a positive correlation, but its linear correlation coefficient was almost 1/3 that of U-235 and much less than U. With the possible exception of average elemental uranium, **the average, median and maximum uranium (U and U-235) in-vivo results were all positively correlated with the frequency of monitoring. Though the coefficients were low, indicating weak correlation, the results may suggest that the in-vivo program was driven by exposure potential to uranium[5] (if at all) and not thorium.** This possibility was discussed in SC&A 2010, Section 3.2, which showed that all thorium in-vivo sampling was done at the same time uranium sampling was done, which might suggest it was incidental to uranium instead of focused on thorium operations.

[5] Table 15 shows that the strongest correlations are for U-235, which might indicate the program was actually geared towards workers exposed to enriched uranium.

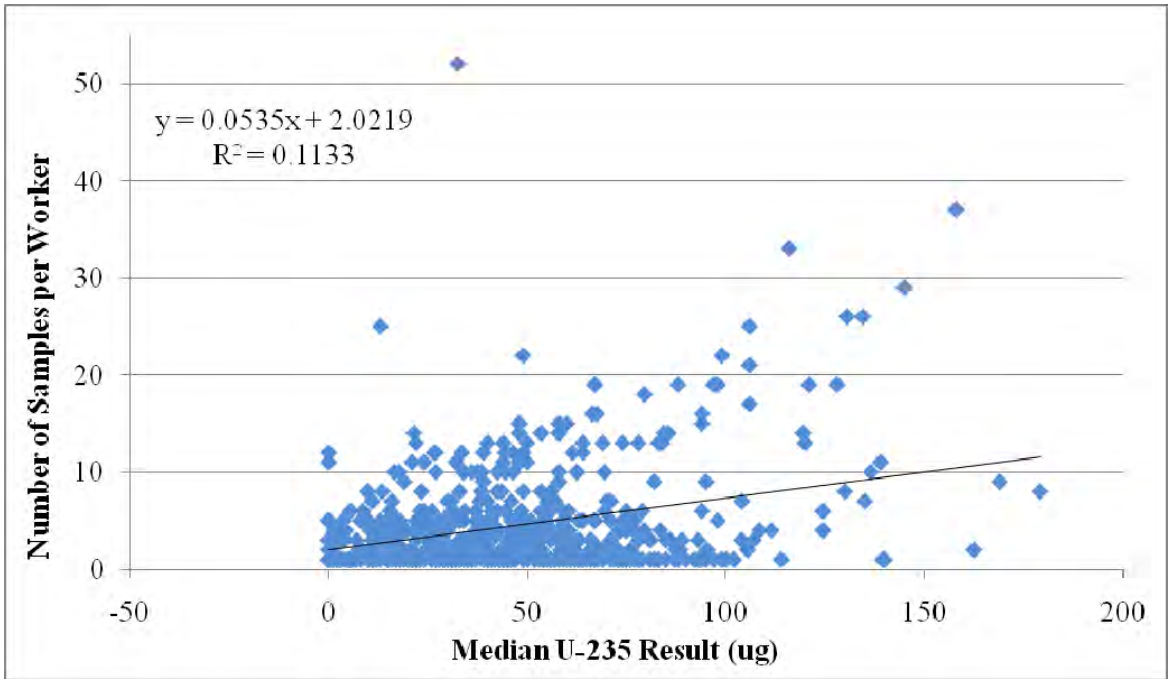

Figure 6. Median U-235 Result versus Number of Samples per Worker (1968–1978)

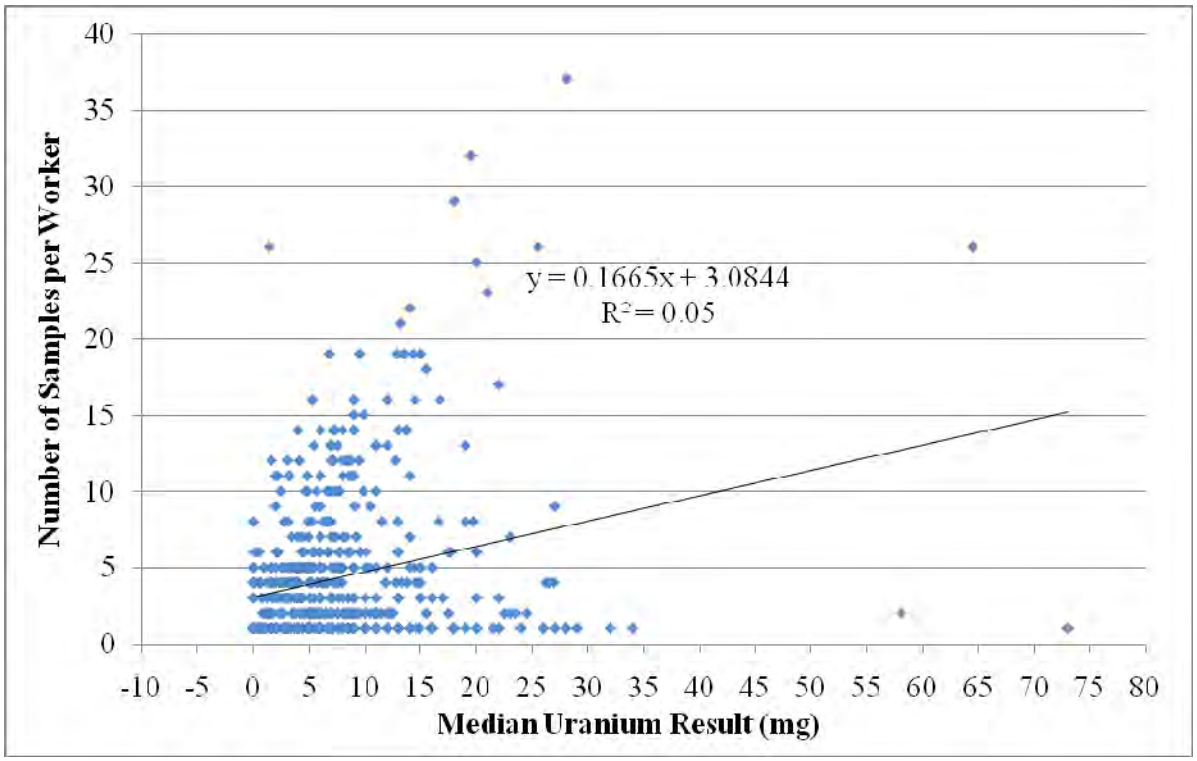

Figure 7. Median Uranium (U) Result versus Number of Samples per Worker (1968–1978)

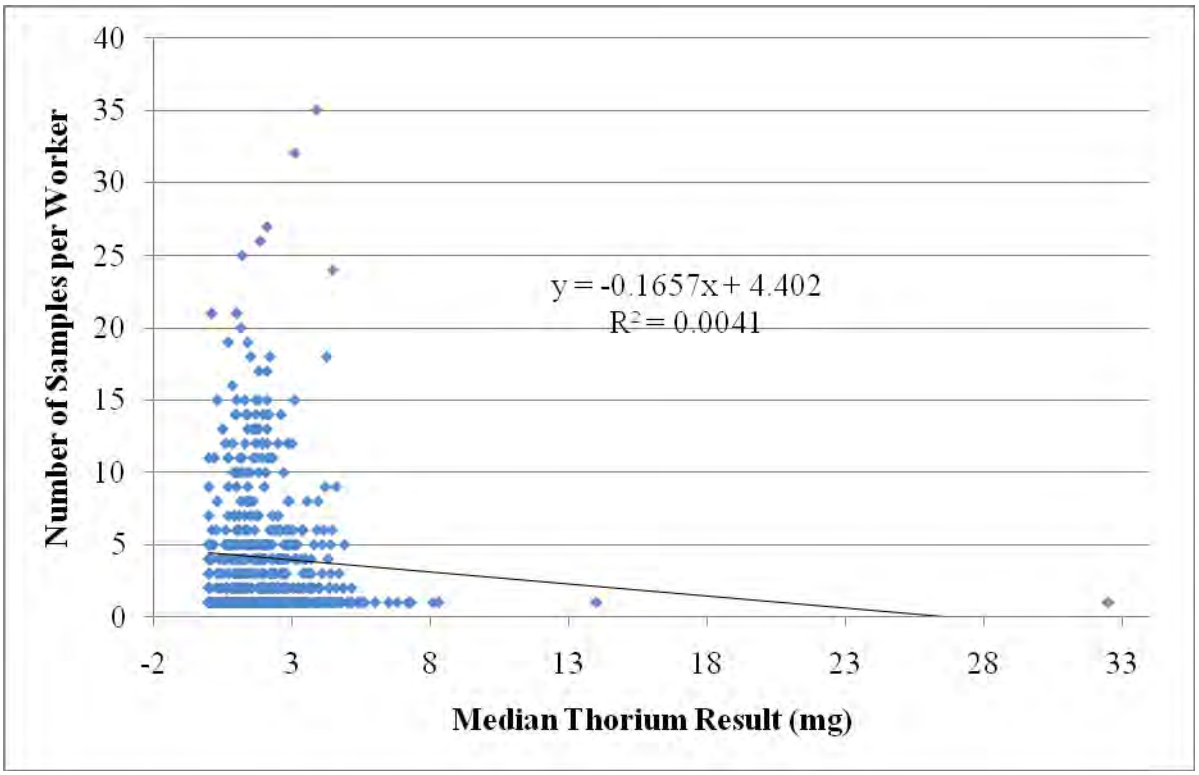

Figure 8. Median Thorium Result versus Number of Samples per Worker (1968–1978)

5.0 REFERENCES

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ATTACHMENT 1: LINEAR CORRELATION BETWEEN THE MAGNITUDE AND FREQUENCY OF SAMPLING FOR INDIVIDUAL WORKERS FOR ALL IN-VIVO RADIONUCLIDES

While Section 2.0 of this report concentrated on the uranium and thorium monitoring during the period of thorium production (1968–1978), this attachment will present all of the in-vivo data for all periods of in-vivo measurements. As outlined in Section 2.0, all negative results were assumed to be 'not detectable' and converted to zero to avoid unduly biasing the results. Table 16 displays the linear trend lines and correlation coefficients as calculated by Excel; Figures 9 through 38 display the corresponding linear plots.

Table 16. Excel Calculated Linear Trend Line Formulas and Correlation Coefficients for All Data over All Measured Years

Measured Radionuclide	Linear Trend Line Formula and Correlation Coefficients		
	Average	Median	Maximum
U-235*	y = 0.0436x + 3.2901 R^2 = 0.0743	y = 0.052x + 3.2039 R^2 = 0.0743	y = 0.0151x + 3.6879 R^2 = 0.086
U**	y = 0.0009x + 4.4191 R^2 = 0.0001	y = 0.0048x + 4.3994 R^2 = 0.0007	y = 0.0151x + 3.6879 R^2 = 0.086
Th***	y = -0.0475x + 4.1759 R^2 = 0.0003	y = -0.1657x + 4.402 R^2 = 0.0041	y = 0.6643x + 1.8825 R^2 = 0.1375
Ac-228	y = 0.8626x + 2.8596 R^2 = 0.0059	y = 0.6876x + 2.8728 R^2 = 0.0032	y = 0.9993x + 2.8099 R^2 = 0.0289
Pb-212	y = 13.236x + 2.6644 R^2 = 0.0759	y = 11.96x + 2.7432 R^2 = 0.0541	y = 10.915x + 2.4887 R^2 = 0.1609

* U-235 analysis includes outlier value of 3,635 µg U-235 in 1987, worker was sampled five times the high result was this worker's final sample

** U analysis includes outlier value of 1,186 mg U in 1987, worker was only sampled one time

*** Th analysis includes outlier value of 32.5 mg Th in 1969, worker was only sampled one time

As noted in Table 16, there were three outlier values (taken for U-235, U and Th) in which a worker had an unusually high result with few (sometimes only 1) measurements taken. Since no direct evidence could be found to invalidate these results, they are included in the Figures 9–38 analyses. However, to give the reader an idea of how the linear correlations change if those three samples are omitted, the linear trend lines and associated correlation coefficients are recalculated in Table 17. As seen in Table 17, the correlations increase markedly for the maximum uranium (U and U-235) categories, as well as the median uranium (U) category, in comparison to Table 16 values. The correlation between the maximum thorium values increased, though the average and median correlations remained slightly negative.

Table 17. Excel Calculated Linear Trend Line Formulas and Correlation Coefficients for All Data over All Measured Years Excluding Three Outlier Measurements

Measured Radionuclide	Linear Trend Line Formula and Correlation Coefficients		
	Average	Median	Maximum
U-235	y = 0.0617x + 2.8509 R^2 = 0.1045	y = 0.052x + 3.2032 R^2 = 0.0744	y = 0.0638x + 1.4554 R^2 = 0.3613
U	y = 0.0009x + 4.4191 R^2 = 0.0001	y = 0.3219x + 2.9252 R^2 = 0.0786	y = 0.2417x + 2.154 R^2 = 0.2959
Th	y = -0.0183x + 4.1133 R^2 = 3E-05	y = -0.2155x + 4.4886 R^2 = 0.0042	y = 0.8224x + 1.392 R^2 = 0.1743

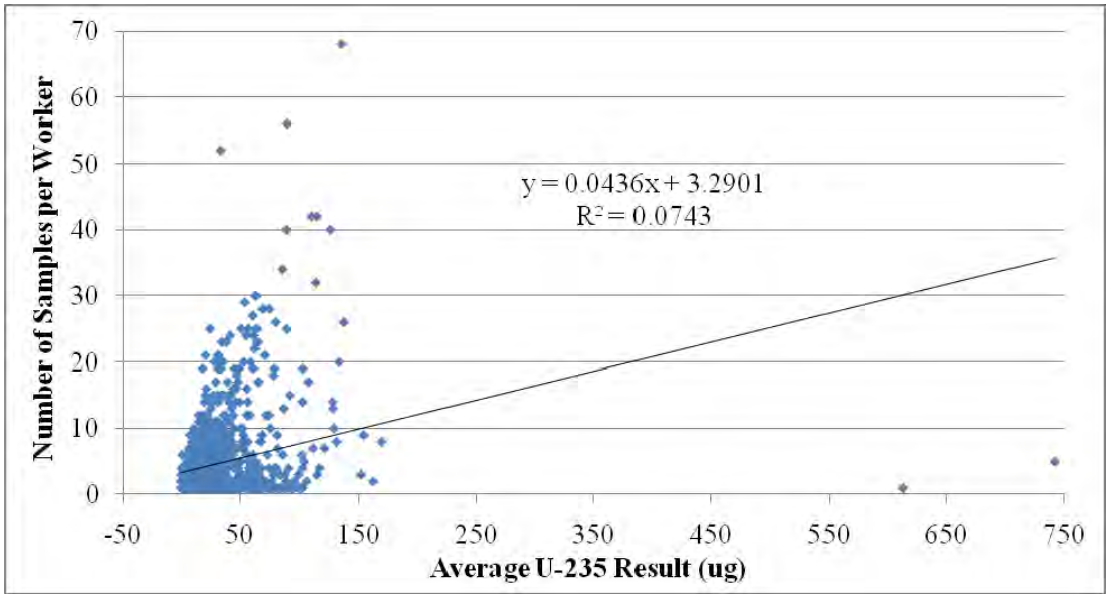

Figure 9. Average U-235 Result versus Number of Samples per Worker

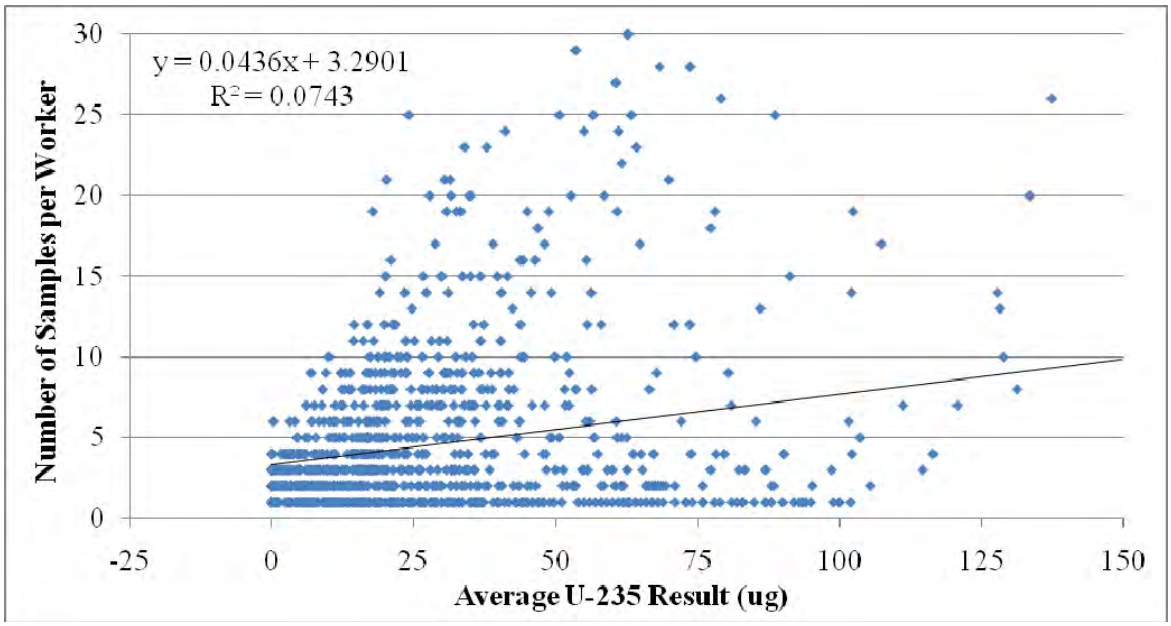

Figure 10. Average U-235 Result versus Number of Samples per Worker (scales truncated)

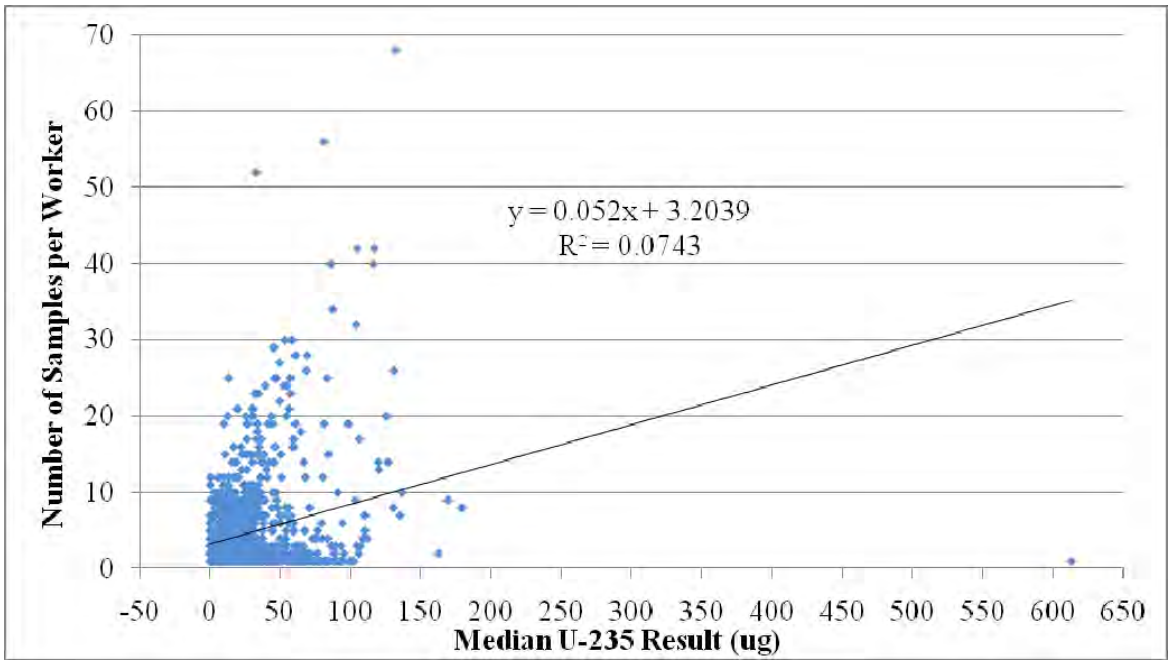

Figure 11. Median U-235 Result versus Number of Samples per Worker

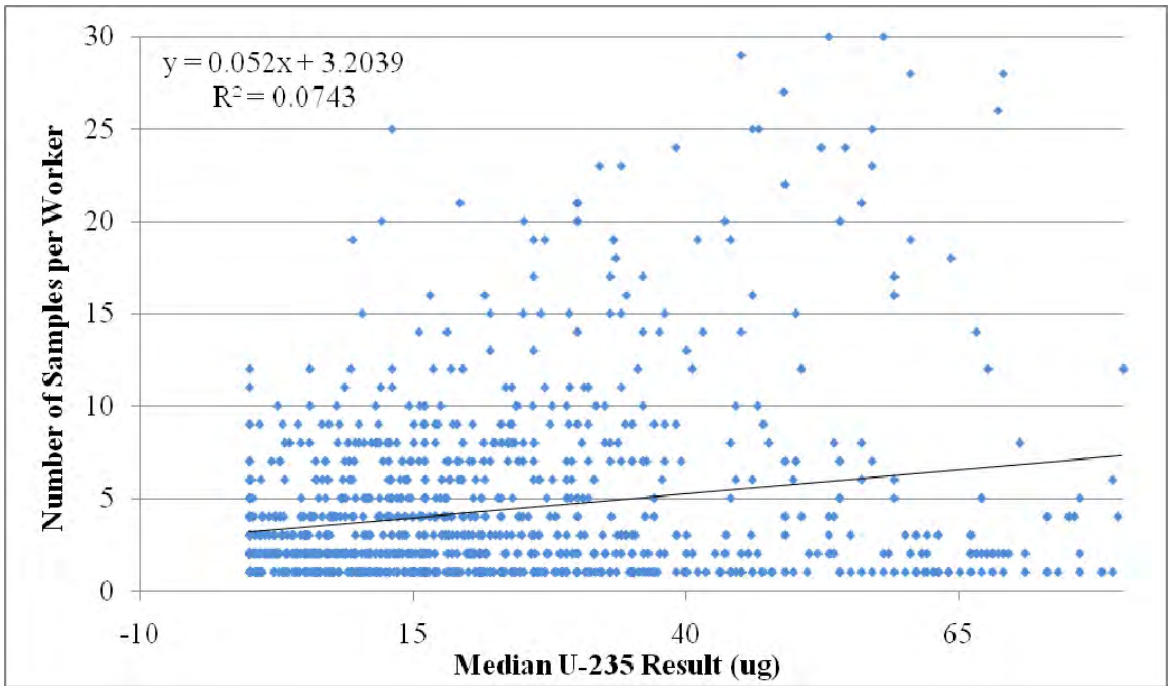

Figure 12. Median U-235 Result versus Number of Samples per Worker (scales truncated)

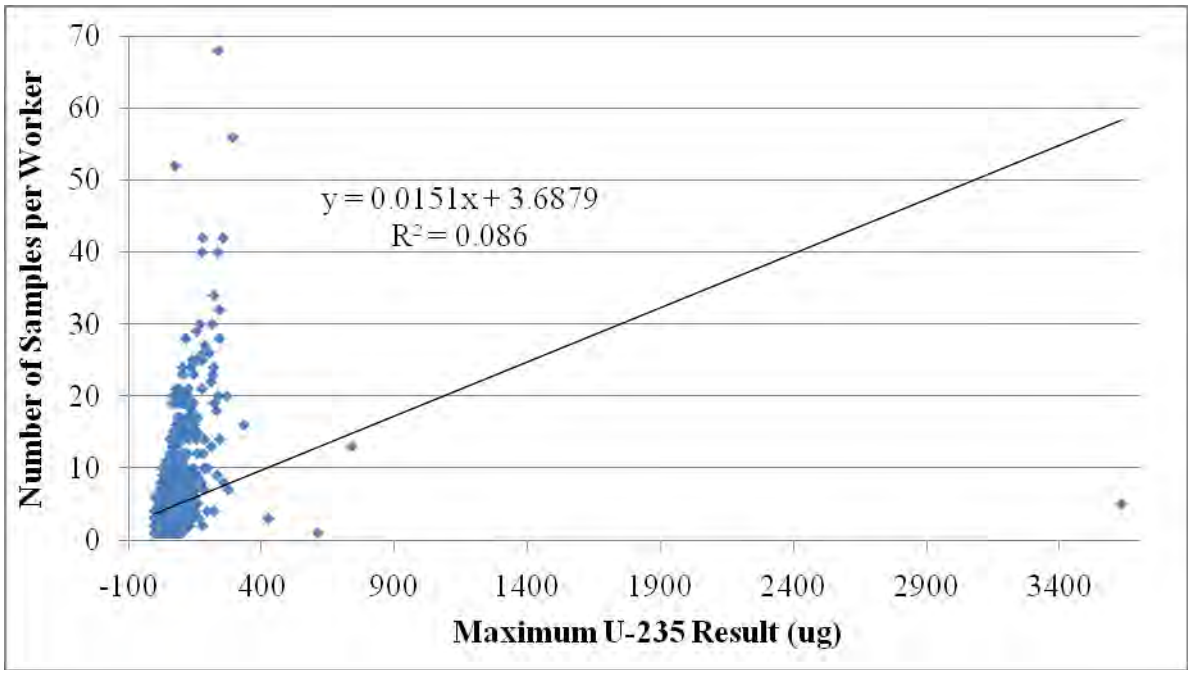

Figure 13. Maximum U-235 Result versus Number of Samples per Worker

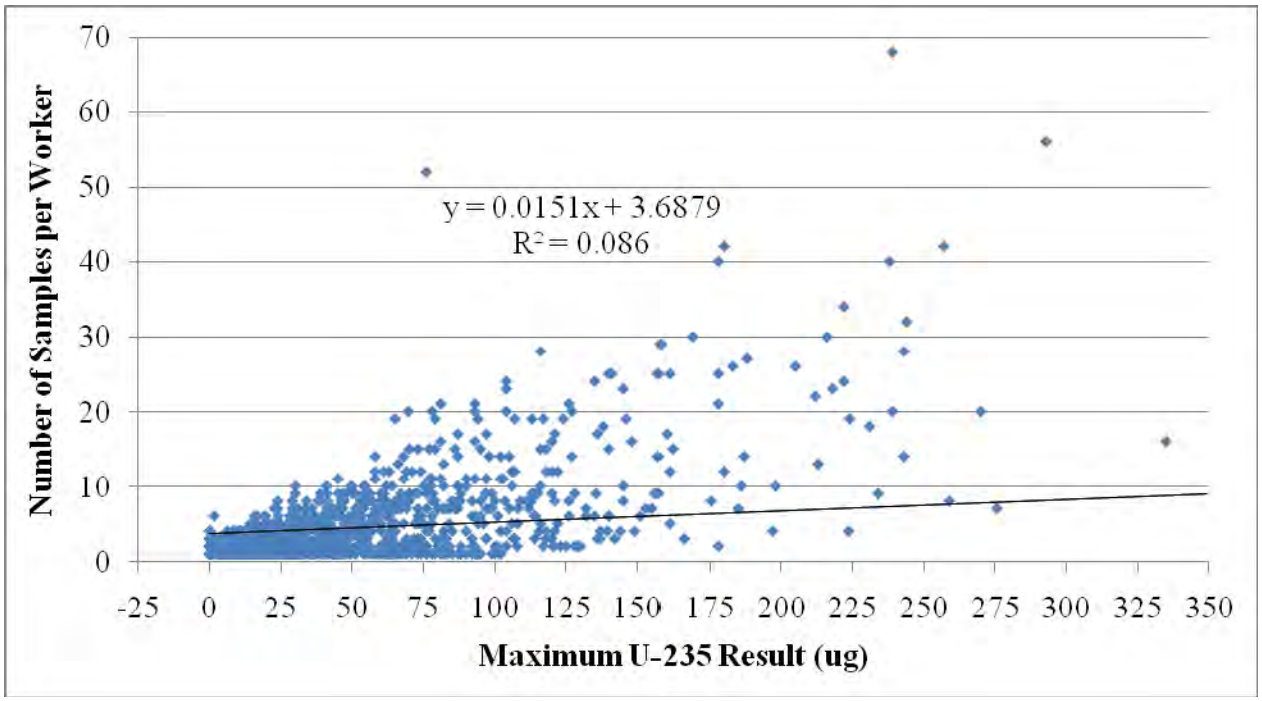

Figure 14. Maximum U-235 Result versus Number of Samples per Worker (scales truncated)

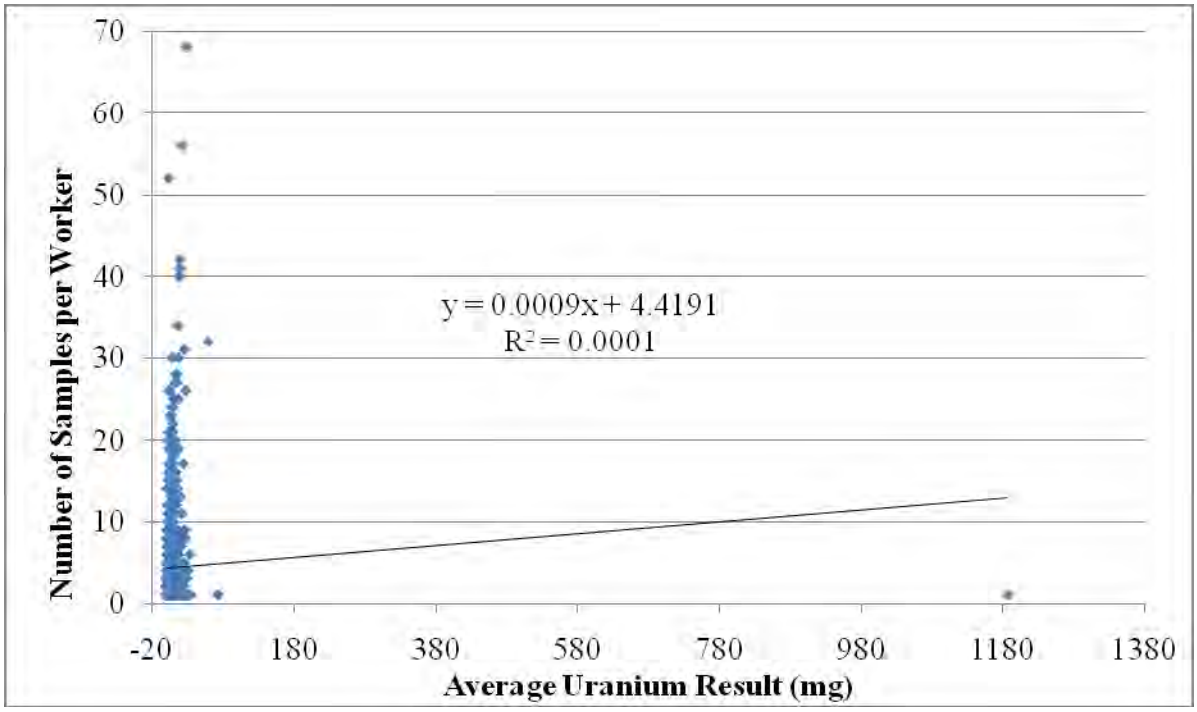

Figure 15. Average Uranium Result versus Number of Samples per Worker

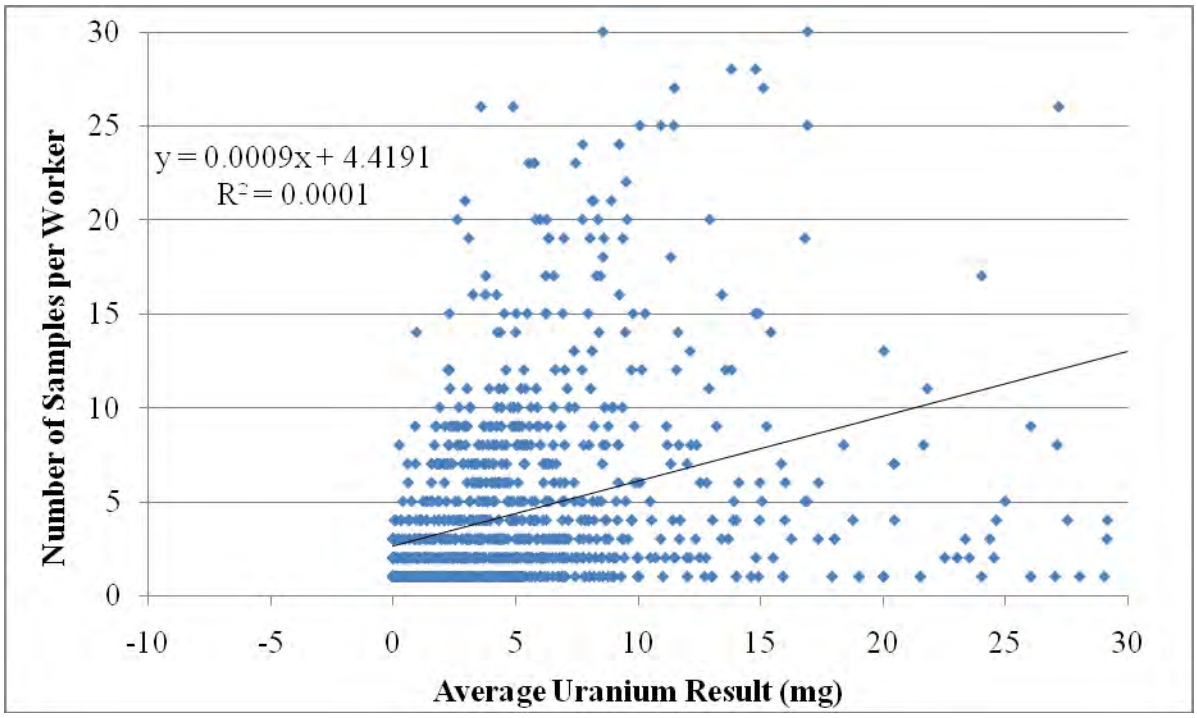

Figure 16. Average Uranium Result versus Number of Samples per Worker (scales truncated)

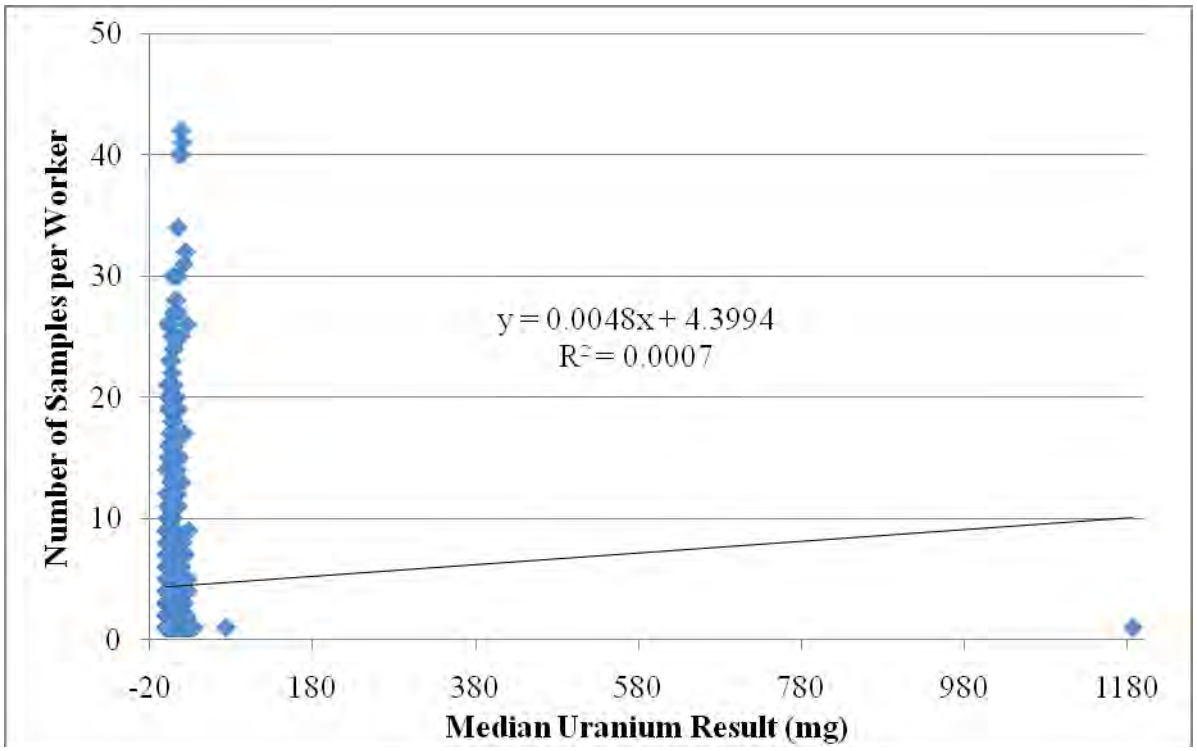

Figure 17. Median Uranium Result versus Number of Samples per Worker

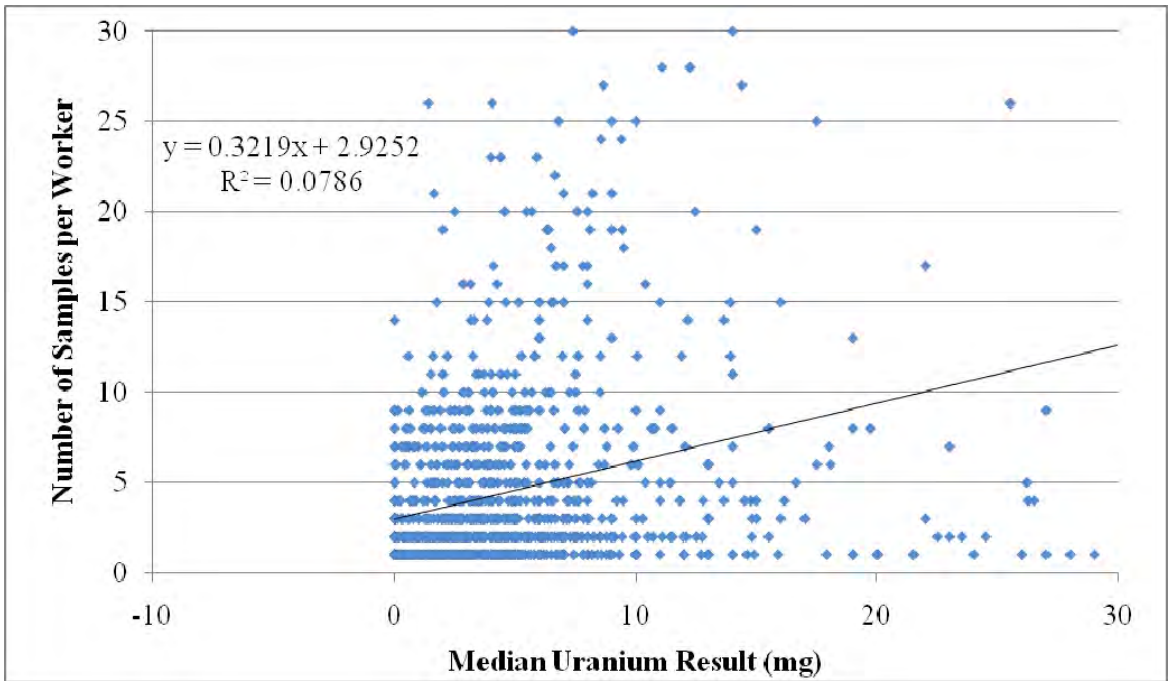

Figure 18. Median Uranium Result versus Number of Samples per Worker (scales truncated)

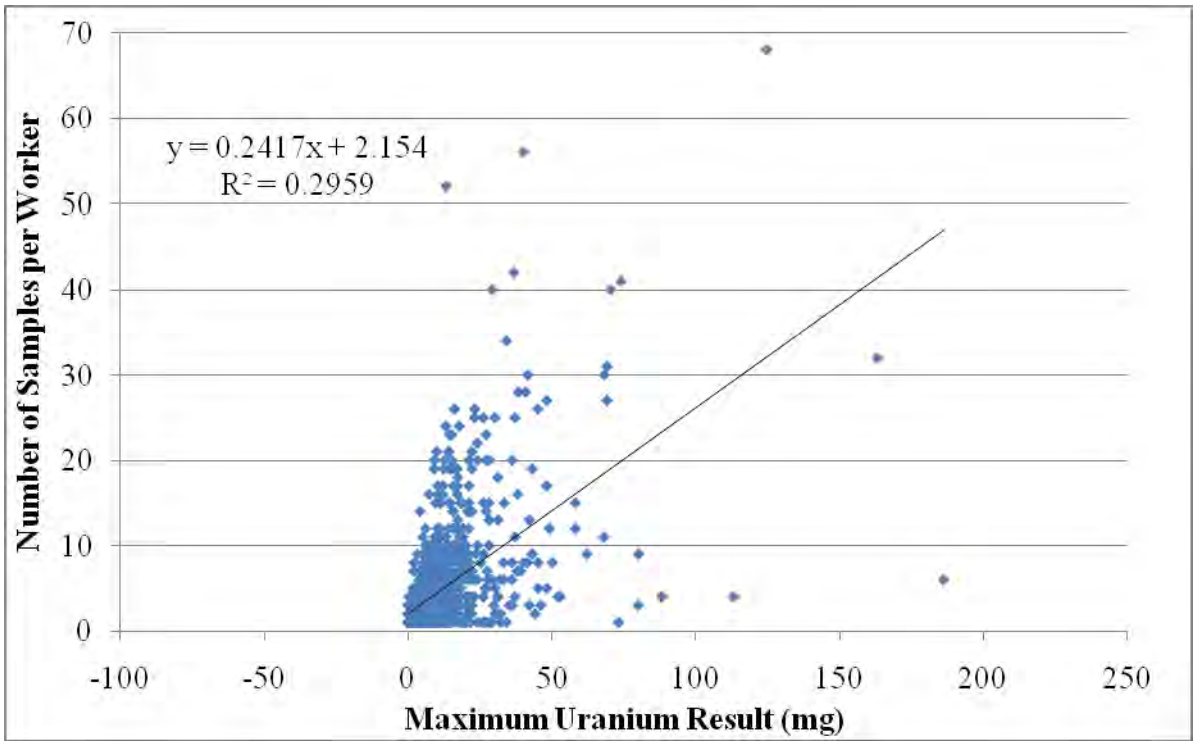

Figure 19. Maximum Uranium Result versus Number of Samples per Worker

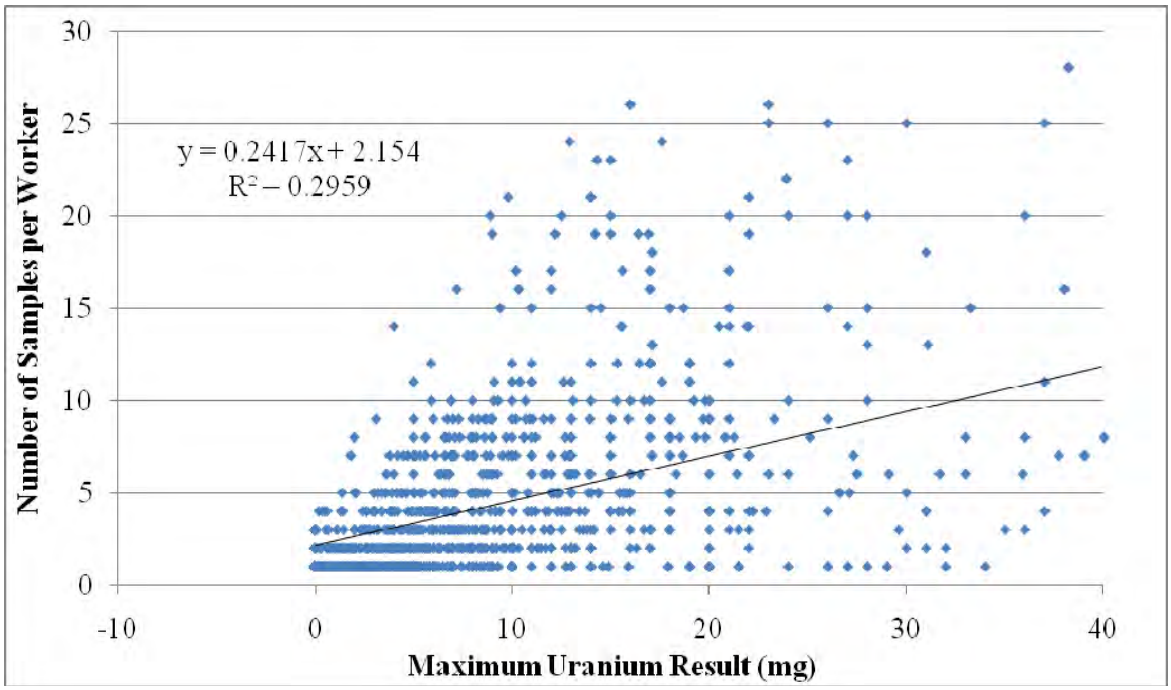

Figure 20. Maximum Uranium Result versus Number of Samples per Worker (scales truncated)

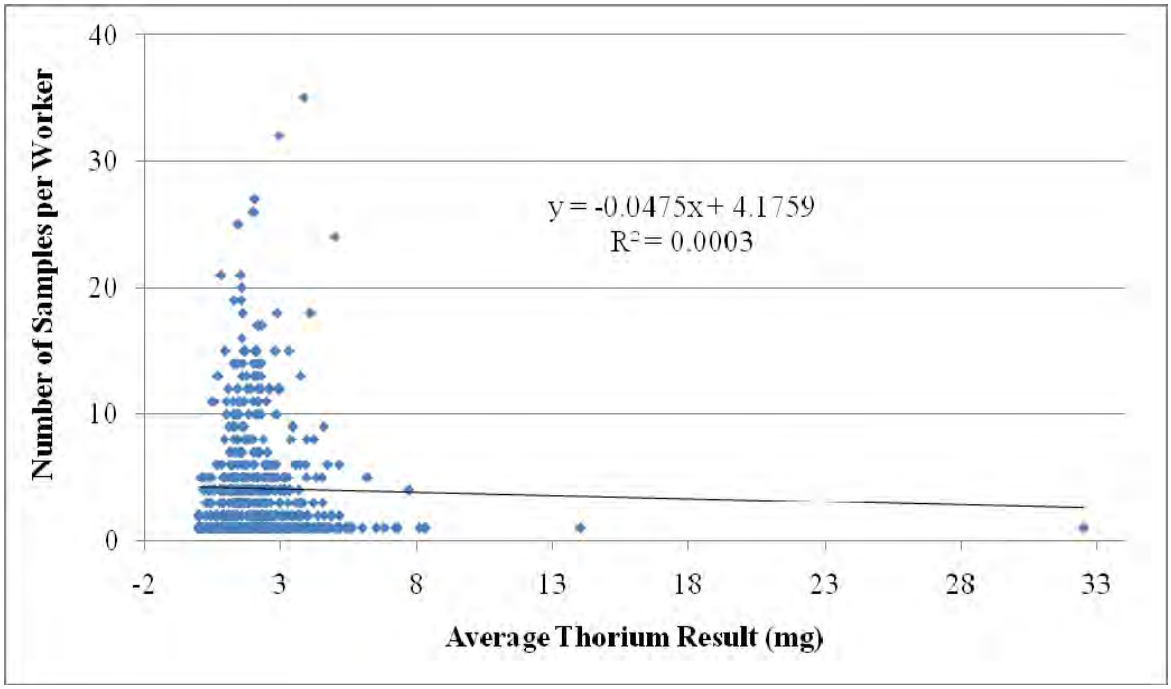

Figure 21. Average Thorium Result versus Number of Samples per Worker

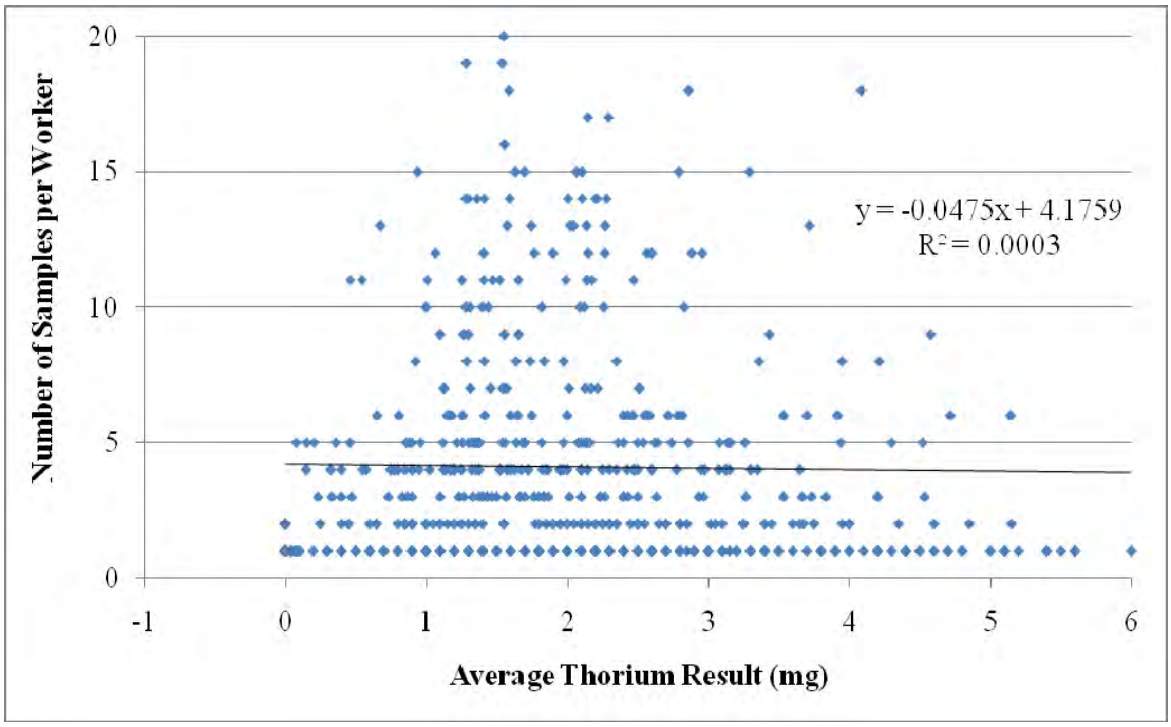

Figure 22. Average Thorium Result versus Number of Samples per Worker (scales truncated)

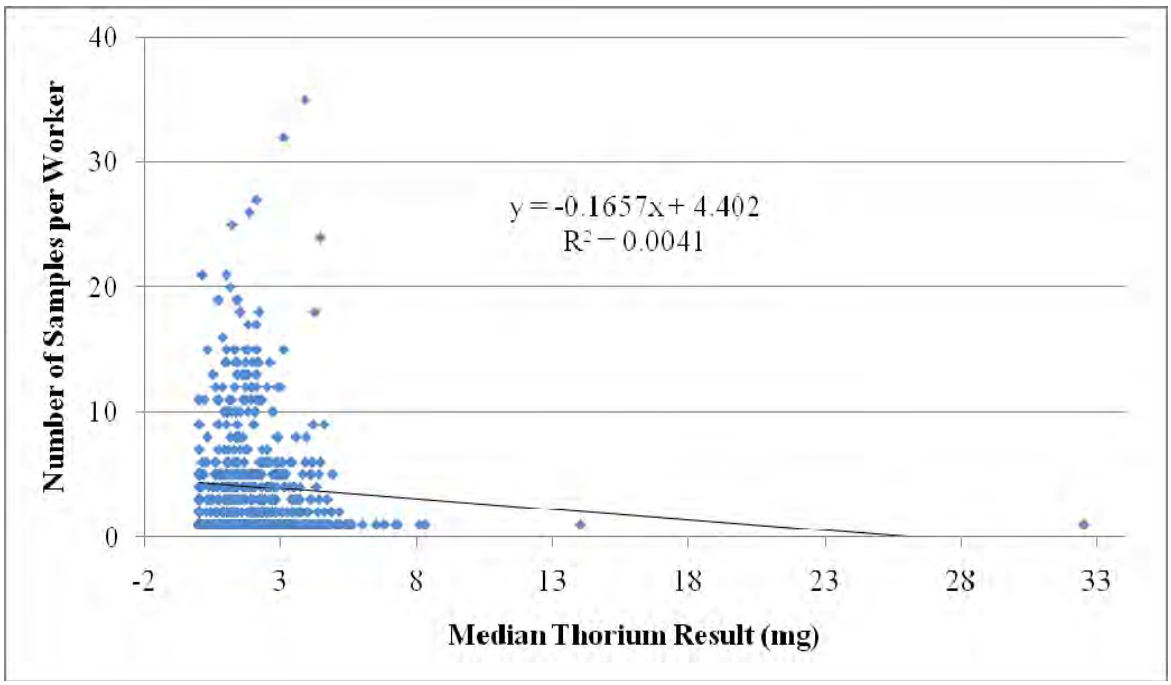

Figure 23. Median Thorium Result versus Number of Samples per Worker

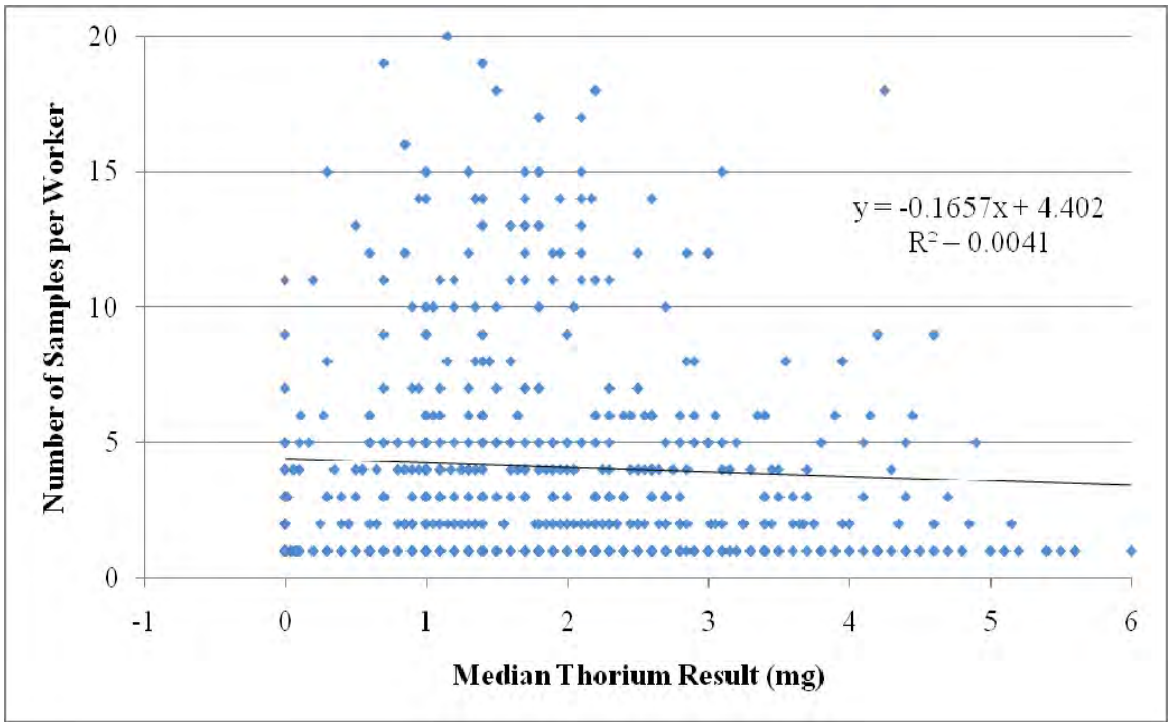

Figure 24. Median Thorium Result versus Number of Samples per Worker (scales truncated)

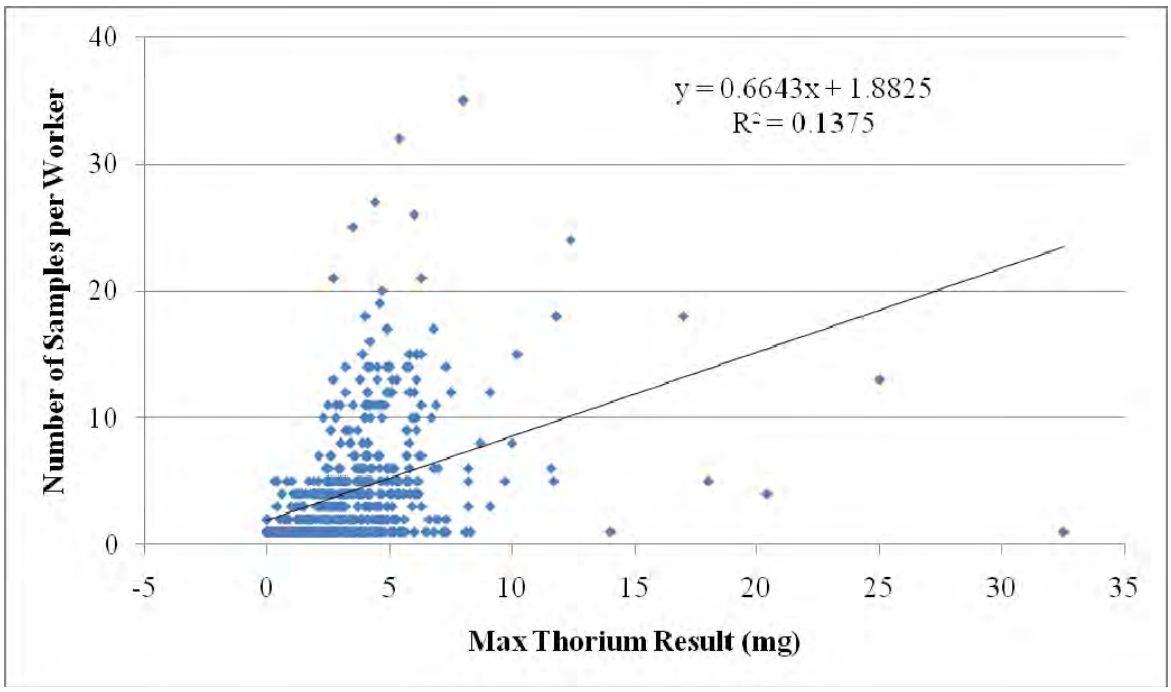

Figure 25. Maximum Thorium Result versus Number of Samples per Worker

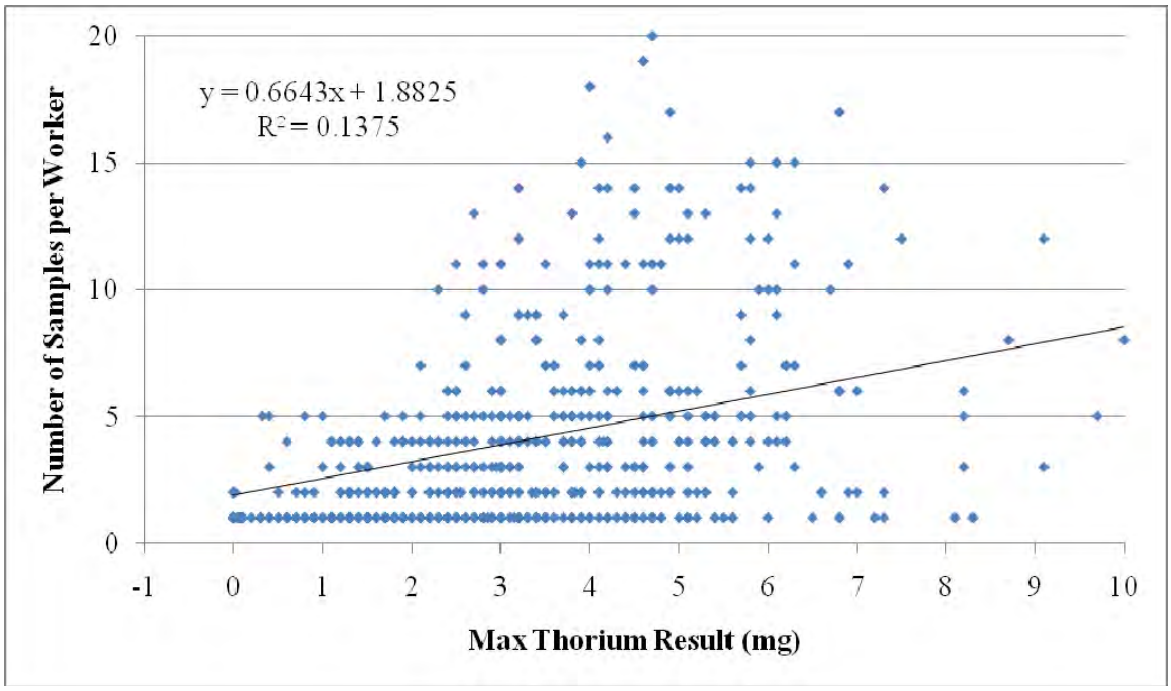

Figure 26. Maximum Thorium Result versus Number of Samples per Worker (scales truncated)

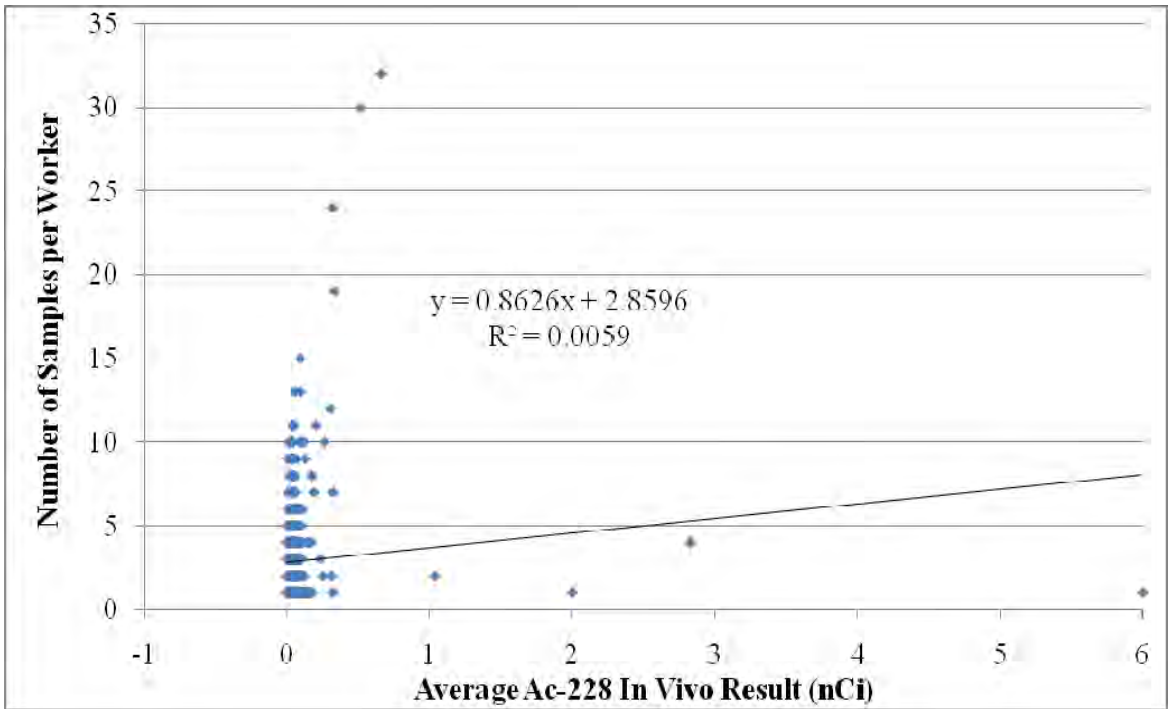

Figure 27. Average Actinium Result versus Number of Samples per Worker

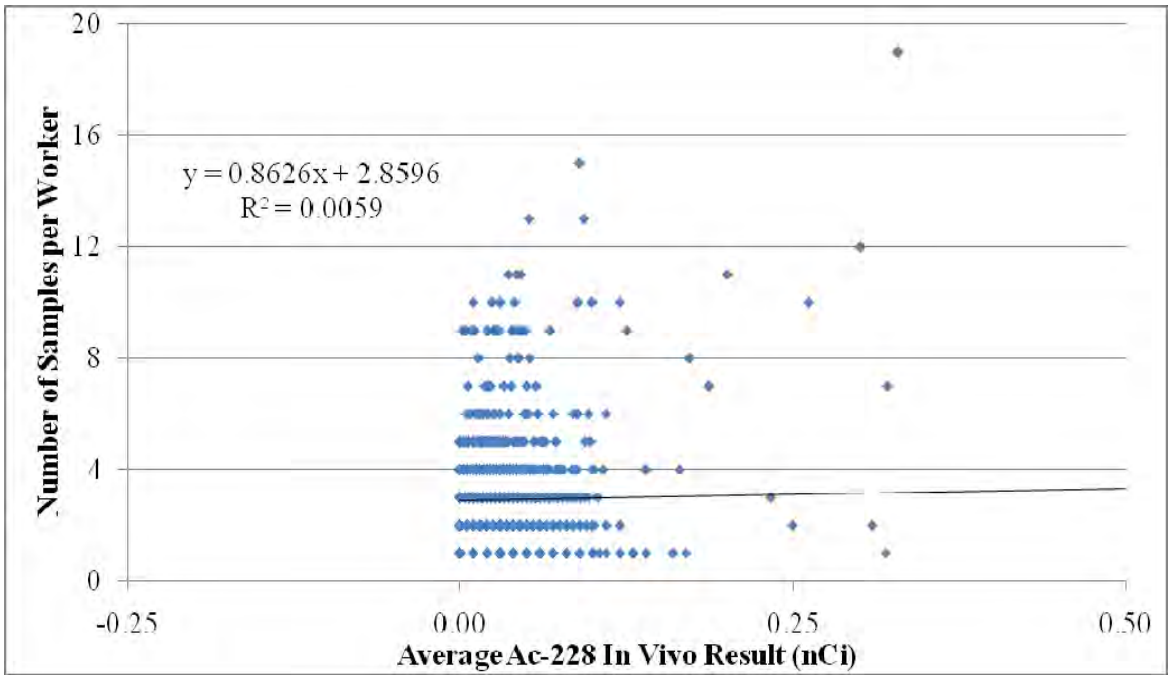

Figure 28. Average Actinium Result versus Number of Samples per Worker (scales truncated)

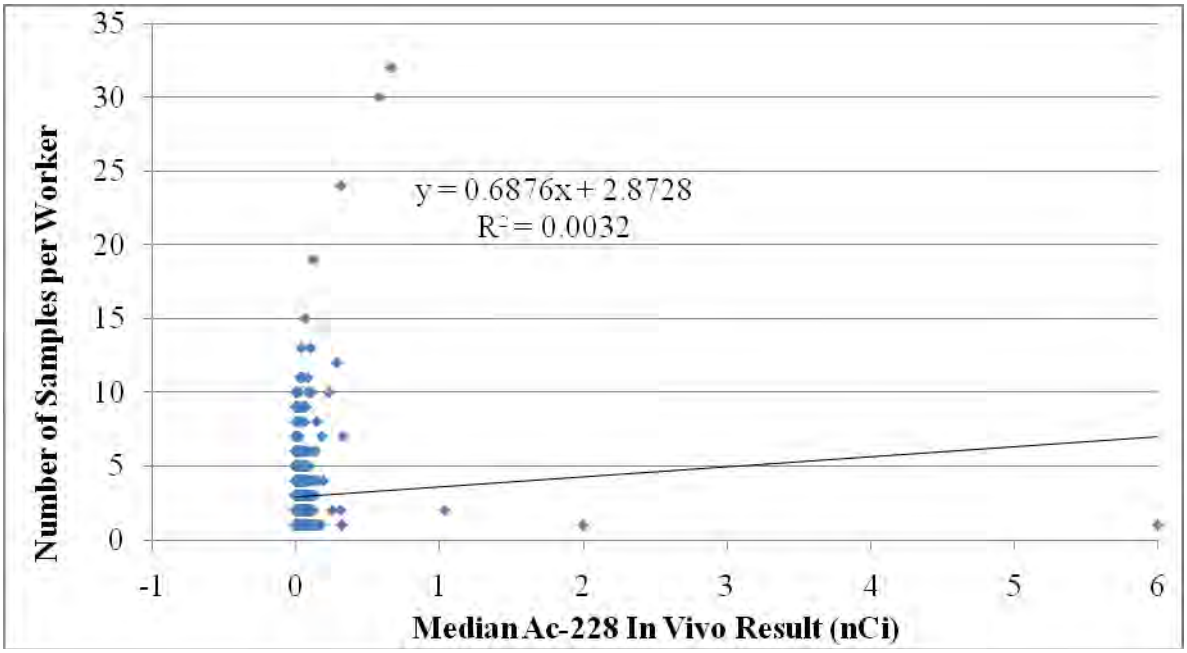

Figure 29. Median Actinium Result versus Number of Samples per Worker

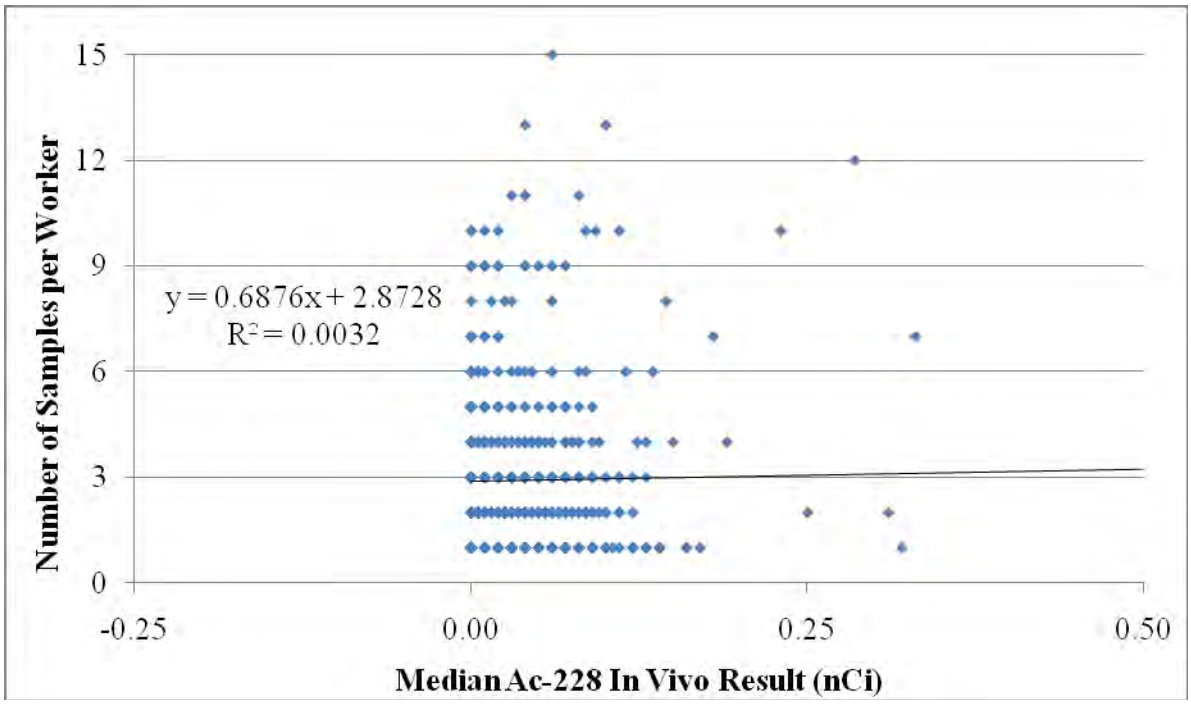

Figure 30. Median Actinium Result versus Number of Samples per Worker (scales truncated)

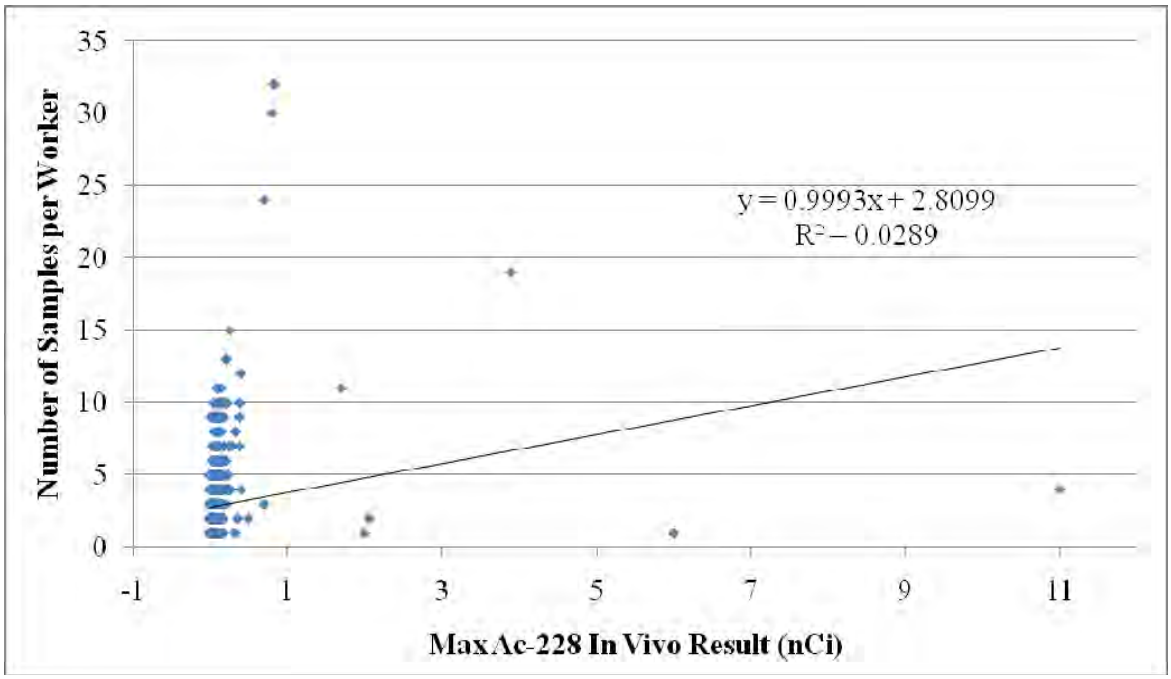

Figure 31. Maximum Actinium Result versus Number of Samples per Worker

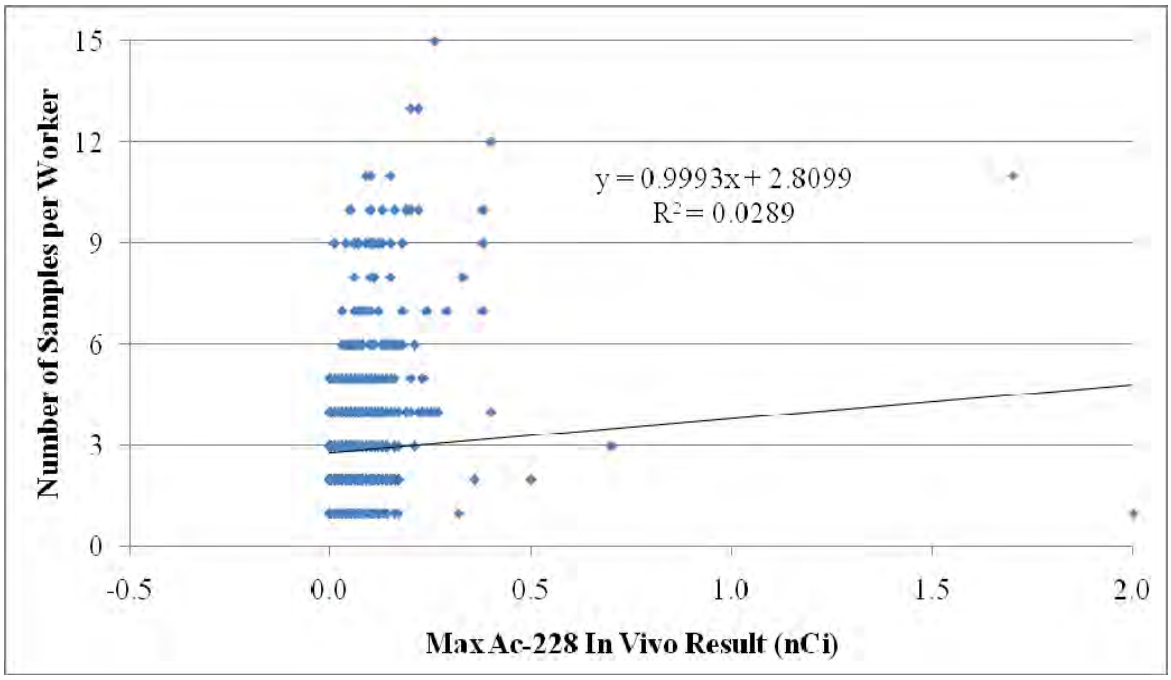

Figure 32. Maximum Actinium Result versus Number of Samples per Worker (scales truncated)

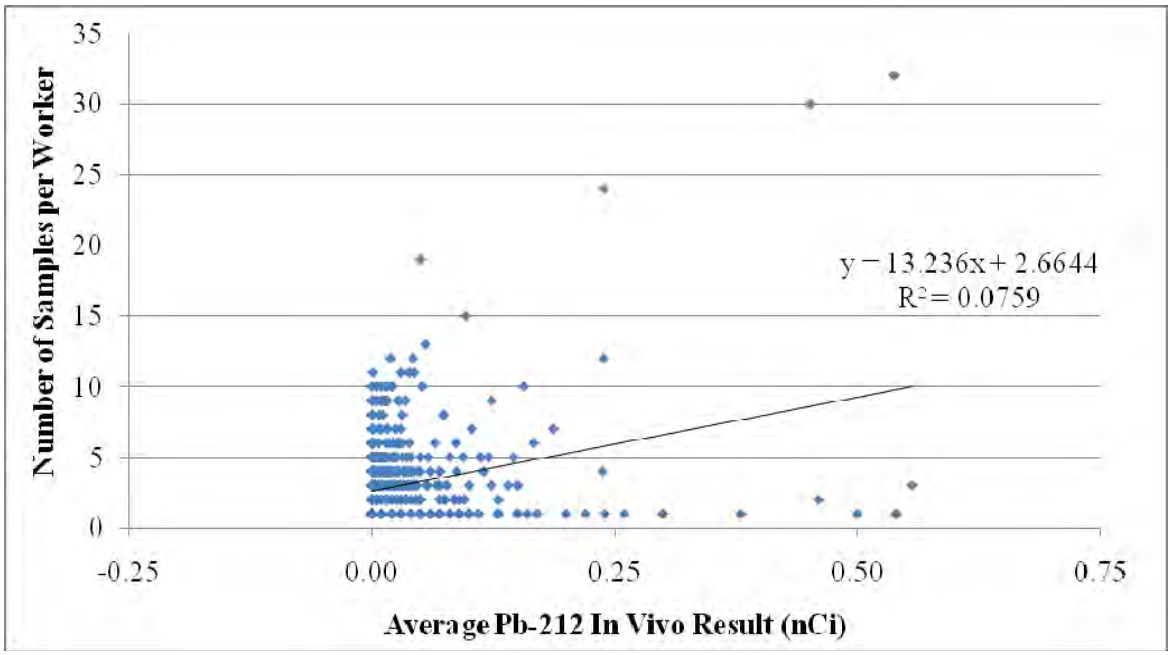

Figure 33. Average Pb-212 Result versus Number of Samples per Worker

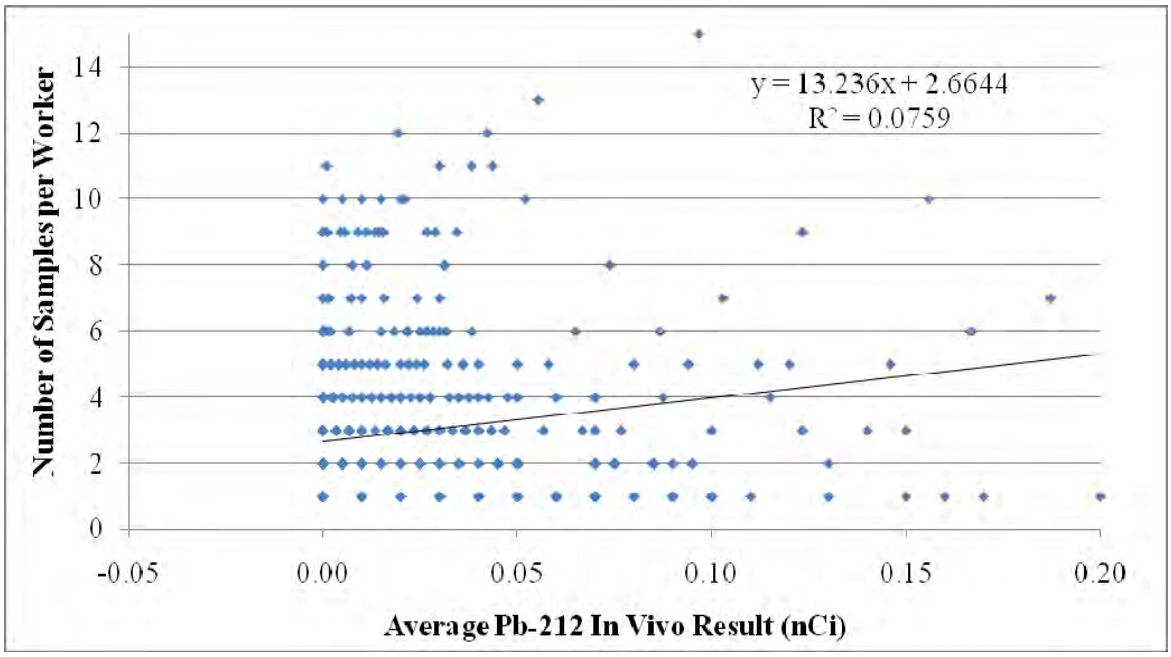

Figure 34. Average Pb-212 Result versus Number of Samples per Worker (scales truncated)

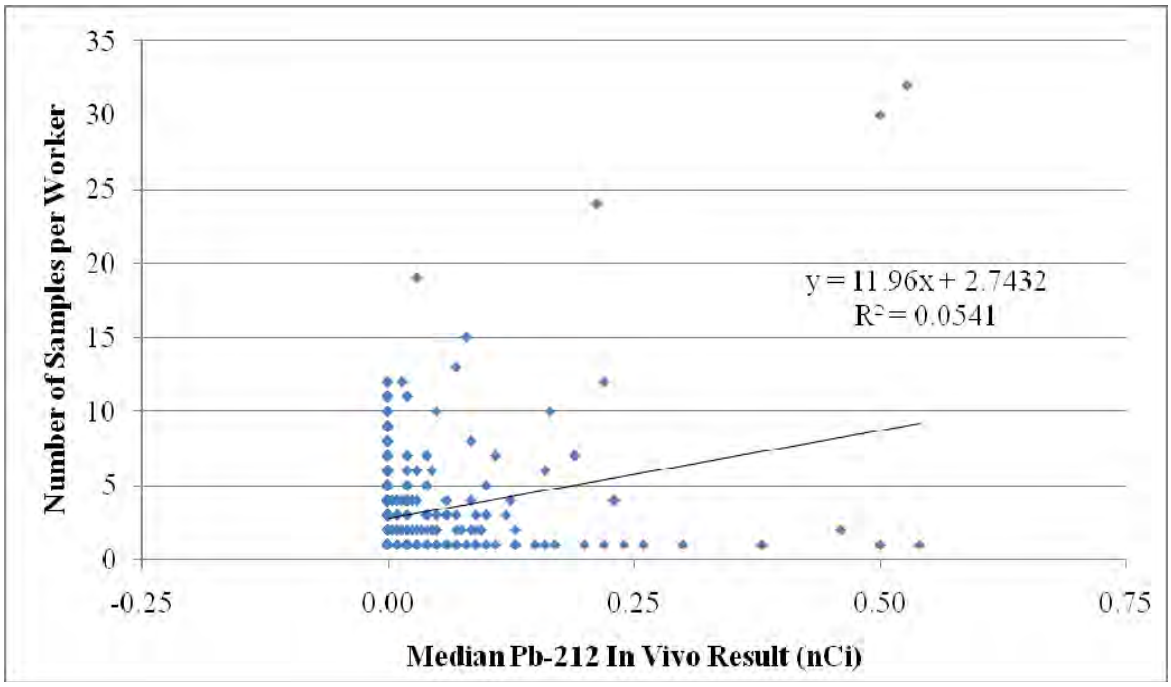

Figure 35. Median Pb-212 Result versus Number of Samples per Worker

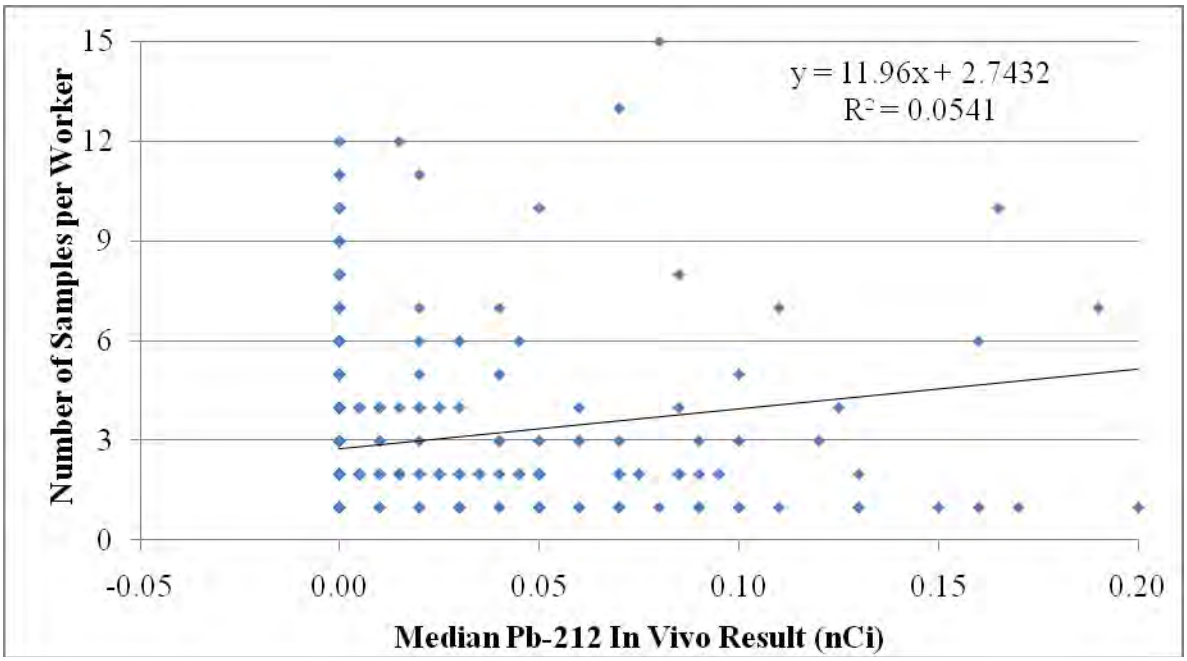

Figure 36. Median Pb-212 Result versus Number of Samples per Worker (scales truncated)

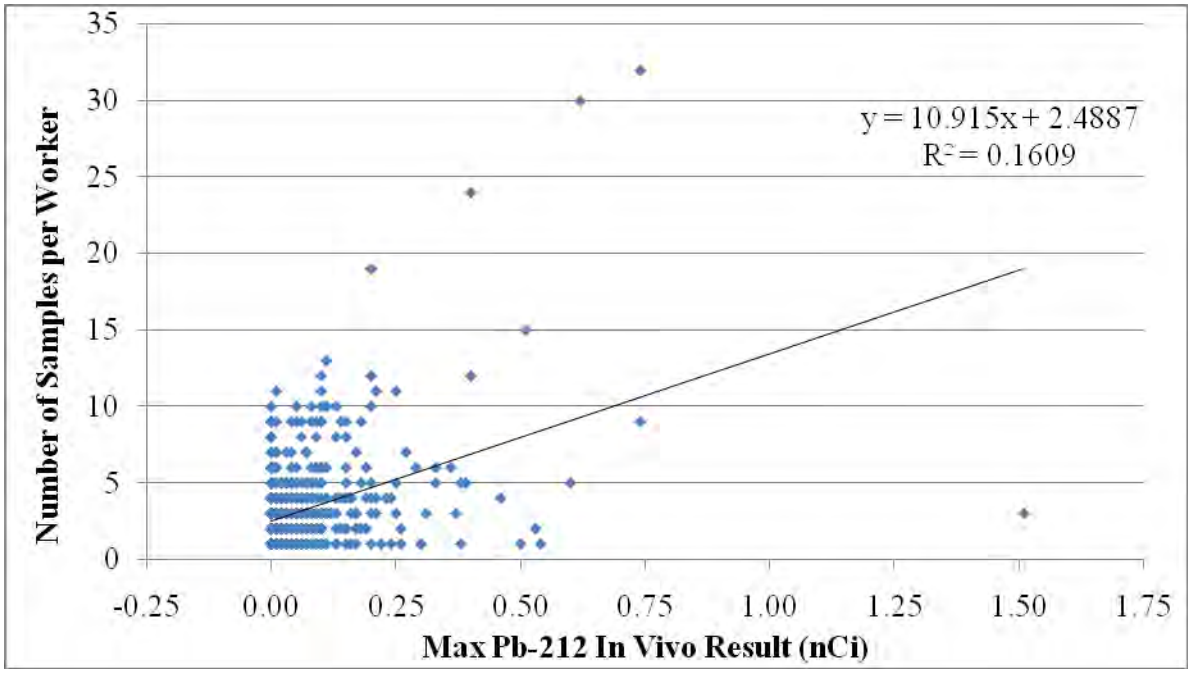

Figure 37. Maximum Pb-212 Result versus Number of Samples per Worker

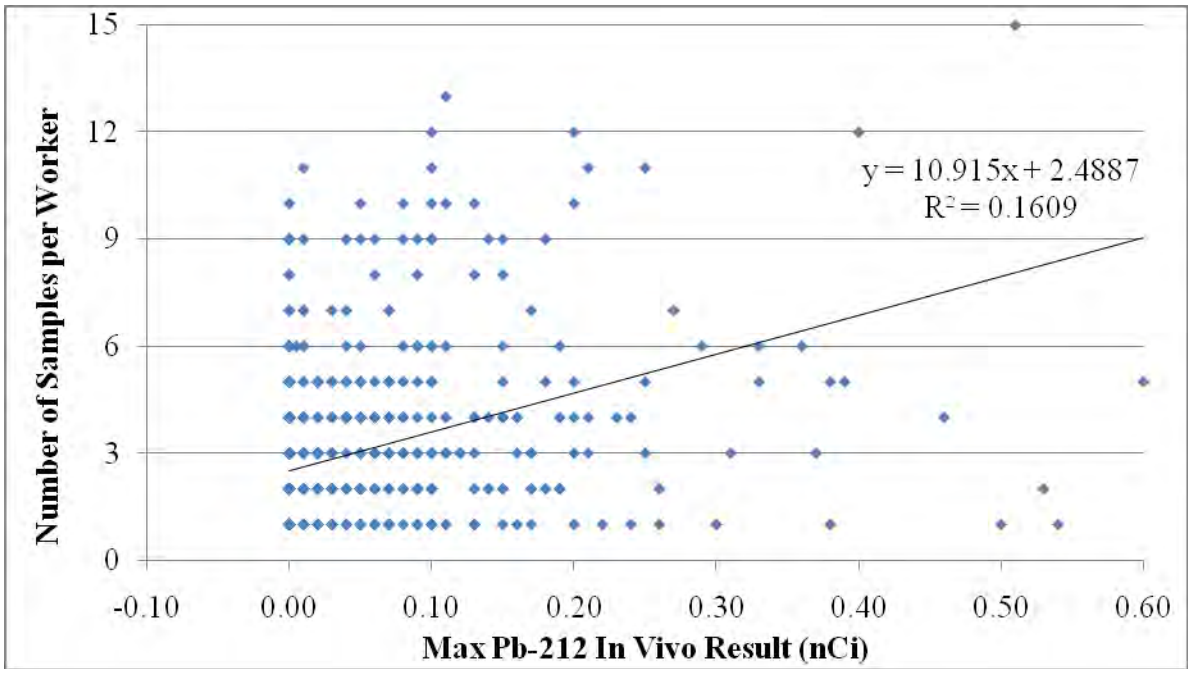

Figure 38. Maximum Pb-212 Result versus Number of Samples per Worker (scales truncated)