Draft

Advisory Board on Radiation and Worker Health
National Institute for Occupational Safety and Health

A Review of ORAUT-OTIB-0087 for Extremity Doses for Mound Exposures to Plutonium-238

Contract No. 75D30119C04183
Document No. SCA-TR-2023-PR087, Revision 0

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April 21, 2023

SC&A, Inc. technical support for the Advisory Board on Radiation and Worker Health's review of NIOSH dose reconstruction program

Document title	A Review of ORAUT-OTIB-0087 for Extremity Doses for Mound Exposures to Plutonium-238
Document number	SCA-TR-2023-PR087
Revision number	0 (Draft)
Supersedes	NA
Effective date	April 21, 2023
Task manager	Kathleen Behling [signature on file]
Project manager	Bob Barton, CHP [signature on file]
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Record of revisions

Revision number	Effective date	Description of revision
0 (Draft)	4/21/2023	Initial issue

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Abbreviations and Acronyms

ABRWH	Advisory Board on Radiation and Worker Health
DOE	U.S. Department of Energy
DR	dose reconstruction
EE	energy employee
FP	fuel processing
LiF	lithium-fluoride
mrem	millirem
NIOSH	National Institute for Occupational Safety and Health
n/p	neutron-to-photon
NTA	nuclear track emulsion, type A
ORAUT	Oak Ridge Associated Universities Team
Pu	plutonium
TLD	thermoluminescent dosimeter
WB	whole-body
W(th)	watts-thermal

1 Statement of Purpose

To support dose reconstruction (DR), the National Institute for Occupational Safety and Health (NIOSH) and the Oak Ridge Associated Universities Team (ORAUT) assembled a large body of guidance documents, workbooks, computer codes, and tools. One of those documents is ORAUT-OTIB-0087, revision 00, "Extremity Doses for Mound Exposures to Plutonium-238" (NIOSH, 2017; "OTIB-0087"), which provides information about and comparison of whole-body (WB), wrist, and finger doses. This information may be used to determine ratios to assist in the assignment of extremity doses. Some energy employees (EEs) at Mound were only assigned WB dosimetry. However, the work they performed may have included handling or working around plutonium (Pu)-238, and it would be expected that the dose to the extremities (forearm, wrist, hand, or finger) would be elevated in comparison with the WB dose. If an EE's extremity dosimeter results are available, those results should be used to assign dose to the cancer site on the extremity. If not, the extremity-to-WB ratio applied to the WB dose can be used to determine the dose to the cancer site on the extremity.

In October 2022, SC&A was tasked to review ORAUT-OTIB-0087, revision 00 (NIOSH, 2017).

2 NIOSH's General Approach to Determining Extremity dose

2.1 Source of data

Mound initiated a study in September 1972 to determine the need for extremity monitoring for personnel involved in Pu-238 operations at the site (Bigler, 1973). Wrist badges suitable for determining both neutron exposure using nuclear track emulsion, type A (NTA) film and gamma exposure using lithium-fluoride (LiF) thermoluminescent dosimeters (TLDs) were selected. The workers who performed the operations were monitored for various lengths of time ranging from 2 to 22 weeks with a 2-week dosimeter exchange frequency.

A study (Bigler & Phillabaum, 1973) was also performed in 1972 and 1973 with wrist and WB gamma and neutron dosimeters during work in gloveboxes where the workers were wearing leaded rubber gloves. The monitoring approach for detecting the gamma and neutron dose used the same monitoring approach (i.e., LiF TLDs and NTA film, respectively) as the other study. This study also involved taping TLDs to the fingertips on the second or third finger of each hand to be able to determine the gamma dose to the fingertips. The number of days the dosimetry was worn ranged from 3 to 10 days.

NIOSH used the information in these reports, "Extremity Monitoring Study of Personnel in Plutonium Operations" (Bigler, 1973) and "Wrist and Fingertip Dose Measurements for Plutonium-238 Processing Operations" (Bigler & Phillabaum, 1973), to determine the ratios of left wrist-to-WB and right wrist-to-WB for gamma and neutron exposures. Ratios for left finger-to-left wrist and right finger-to-right wrist gamma ratios for a limited number of applications were also developed.

2.2 NIOSH's analysis of data in ORAUT-OTIB-0087

NIOSH used the Akaike information criterion to estimate the quality of the model relative to other models for the wrist-to-WB data available from Bigler (1973) and Bigler and Phillabaum

(1973). The following sections summarize NIOSH's analysis of the gamma and neutron wrist-to-WB dose data.

2.2.1 Wrist-to-whole body gamma dosimetry data analysis

The wrist-to-WB gamma dosimetry data for the left and right wrist are summarized in table 5-1 of OTIB-0087 for 28 employees covering nine different operations involving the handling of Pu-238 at Mound. NIOSH found that the wrist-to-WB gamma dosimetry data were best represented using a Weibull distribution. Figure 5-1 of OTIB-0087 provides a summary plot of the fit comparison for the gamma wrist-to-WB ratio. NIOSH determined the Weibull distribution values were 1.3295 (shape of curve), 1.9271 (scale), and 0.3436 (location).

2.2.2 Wrist-to-whole body neutron dosimetry data analysis

The wrist-to-WB neutron dosimetry data for the left and right wrist are summarized in table 5-1 of OTIB-0087 for 28 employees covering nine different operations involving the handling of Pu-238 at Mound. NIOSH found that the wrist-to-WB neutron dosimetry data were best represented using a lognormal distribution. Figure 5-2 of OTIB-0087 provides a summary plot of the fit comparison for the neutron wrist-to-WB ratio. NIOSH determined the most appropriate fit to be a lognormal distribution with a geometric mean of 1.5796 and geometric standard deviation of 2.5414.

2.2.3 Finger-to-wrist gamma dosimetry data analysis

The finger-to-wrist gamma dosimetry data for the left and right hand/wrist are summarized in table 5-2 of OTIB-0087 for six workers covering three different operations involving the handling of Pu-238 at Mound. NIOSH found that since the data are limited, a fit comparison could not be determined; therefore, NIOSH recommends the use of a normal distribution model. From the limited dataset, NIOSH calculated an average left-hand finger-to-wrist ratio of 3.18, with a standard deviation of 0.53, and a right-hand finger-to-wrist ratio of 2.76, with a standard deviation of 0.85. Unless it is known that a worker is right- or left-handed, NIOSH recommends that the higher ratio should be used (i.e., 3.18 with a standard deviation of 0.53).

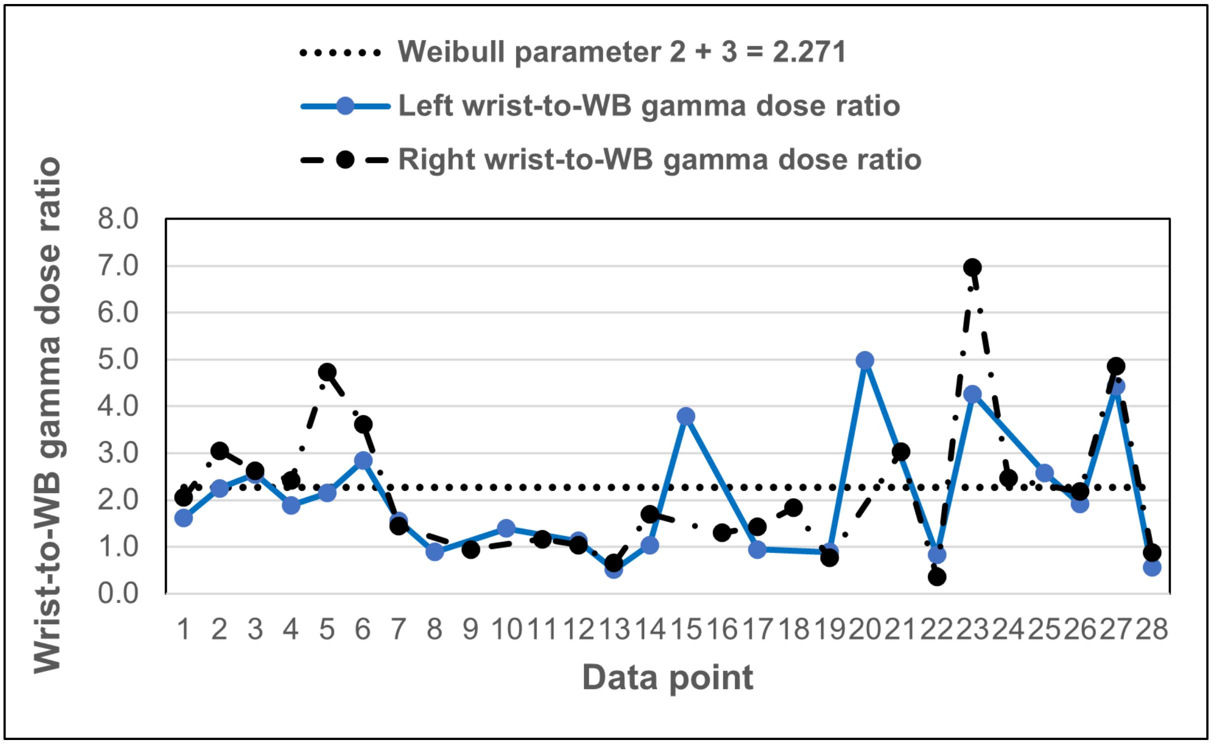
3 SC&A's Review of ORAUT-OTIB-0087

SC&A evaluated the original recorded Mound data, their use in constructing tables 5-1 and 5-2 and figures 5-1 and 5-2 of OTIB-0087, and the DR recommendations in section 6.0 of OTIB-0087. SC&A also performed a statistical analysis of the available data.

3.1 SC&A's evaluation of original Mound data used in OTIB-0087

SC&A reviewed the tabulated Mound data (Bigler, 1973, PDF pp. 177–183; Bigler & Phillabaum, 1973, PDF pp. 203–206). SC&A found that, while the quantity of data was somewhat limited (data from 28 employees for determining wrist-to-WB ratios and data from six employees for determining finger-to-wrist ratios), the measurements were conducted using acceptable dosimetry methods. As illustrated in figure 1 of this report, there were variations in the resulting ratio values listed in table 5-1 of OTIB-0087. Similar results are listed for neutron wrist-to-WB dose ratios.

Figure 1. Wrist-to-WB gamma dose ratios, left and right hand

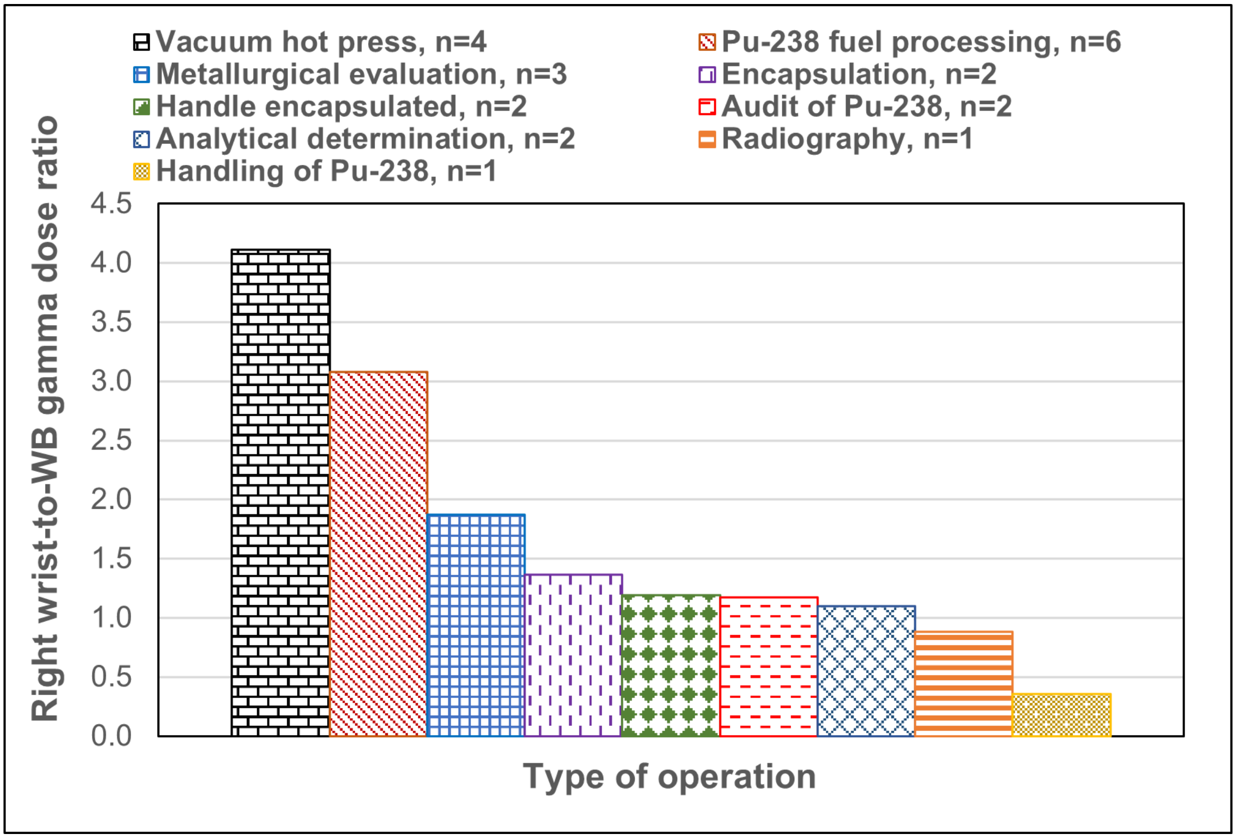


Source: Table 5-1 of OTIB-0087 (NIOSH, 2017).

SC&A reviewed the wrist-to-WB ratio values in view of the potential impact of different fractions of time the worker was exposed to Pu-238 sources compared to the fraction of time spent in the general radiation area. The wrist-to-WB dose data (Bigler & Phillabaum, 1973, PDF p. 205) provide three situations where the fraction of time spent with the Pu-238 sources compared to the total monitoring time was provided. The time fraction ranged from approximately 11 percent to 40 percent. However, the data did not provide any apparent correlation between the fraction of time and the wrist-to-WB ratios for either gamma or neutron exposure. Therefore, SC&A reviewed the wrist-to-WB ratios to determine if there was a general correlation of ratio values to the operation the workers performed.

Figure 2 shows an example of the right wrist-to-WB gamma dose ratios as a function of operation. The number of pairs of right wrist-WB gamma dose data points is indicated by the n = number following the specific handling operation in the figure legend. There was a total of 23 pairs for the right wrist-WB gammas doses because five of the 28 entries were listed as "N/M" (SC&A assumed that that meant "not measured").

Figure 2. Right wrist-to-WB gamma dose ratios as a function of operation



Source: Table 5-1 of OTIB-0087 (NIOSH, 2017).

SC&A obtained similar, but not identical, results for the left wrist-to-WB gamma dose ratios, as well as the left and right wrist-to-WB neutron dose ratios. Tables 1 and 2 summarize the wrist-to-WB dose ratios, from largest to smallest, as a function of operation.

Table 1. Right and left wrist-to-WB gamma dose ratios as a function of operation

Position	Number of pairs of wrist-to-WB data points *	Average right wrist-to-WB gamma dose ratio	Average left wrist-to-WB gamma dose ratio
Vacuum hot press operation of Pu-238 discs	5	4.12	3.30
Pu-238 fuel processing	6	3.08	2.22
Metallurgical evaluations and studies involving encapsulation of Pu-238	4	1.87	2.94
Encapsulation and decontamination of Pu-238 sources	3	1.37	2.37
Handle encapsulated and project Pu-238 sources outside of glovebox and move sources within plant	3	1.19	1.22
Audit of Pu-238 encapsulation process	2	1.18	0.78
Analytical determination of Pu-238 fuel used in sources	3	1.10	1.26

Position	Number of pairs of wrist-to-WB data points *	Average right wrist-to-WB gamma dose ratio	Average left wrist-to-WB gamma dose ratio
Radiography and leak testing of Pu-238 sources	1	0.88	0.56
Handling of Pu-238 neutron sources	1	0.36	0.83

* There were several instances where the right or left wrist dose was listed as "N/A" or "N/M."

Source: Table 5-1 of OTIB-0087 (NIOSH, 2017).

Table 2. Right and left wrist-to-WB neutron dose ratios as a function of operation

Position	Number of pairs of wrist-to-WB data points *	Average right wrist-to-WB neutron dose ratio	Average left wrist-to-WB neutron dose ratio
Metallurgical evaluations and studies involving encapsulation of Pu-238	4	2.94	11.11
Radiography and leak testing of Pu-238 sources	1	2.68	1.61
Vacuum hot press operation of Pu-238 discs	5	2.50	7.26
Pu-238 fuel processing	6	2.09	1.44
Audit of Pu-238 encapsulation process	2	1.78	0.60
Handle encapsulated and project Pu-238 sources outside of glovebox and move sources within plant	3	1.31	1.43
Encapsulation and decontamination of Pu-238 sources	3	1.25	1.16
Analytical determination of Pu-238 fuel used in sources	3	1.19	1.81
Handling of Pu-238 neutron sources	1	0.29	0.50

* There were several instances where the right or left wrist dose was listed as "N/A" or "N/M."

Source: Table 5-1 of OTIB-0087 (NIOSH, 2017).

Tables 1 and 2 indicate that the right and left wrist-to-WB ratios varied according to the type of operation being performed (for both gamma and neutron doses). This relationship is examined in more details in attachment A of this report.

The original Mound data (Bigler, 1973, PDF p. 182; Bigler & Phillabaum, 1973, PDF p. 206) provide lists of derived neutron-to-photon (n/p) ratios from WB, left wrist, and right wrist dose data. The n/p values have a wide range of 0.22 to 12.00; therefore, neutron along with gamma extremity dosimetry is needed because the use of an average n/p value instead of using neutron dosimetry could result in considerable errors in neutron extremity dose assignment.

Finding 1: When applying ratios to other operating periods or DOE sites, NIOSH should have an understanding that the exposure conditions are similar to those used in OTIB-0087

Considering the variations in wrist-to-WB ratio values as a function of operation, it is important when applying the Mound extremity ratio values to DR from other operating periods at Mound or other U.S. Department of Energy (DOE) sites, as recommended in section 1.2 of OTIB-0087, to first ascertain that the conditions of exposure to Pu-238 during the other periods at Mound or at other sites are encompassed by the Mound operations. For example, leaded glove, as was used when the OTIB-0087 measurements were conducted, could influence the resulting ratios. If leaded gloves were not worn during other operational periods at Mound or other sites, the measured ratios might not be applicable.

It should also be noted that SC&A is aware that NIOSH is applying the OTIB-0087 ratios at other DOE sites. SC&A has reviewed a 2020 DR case that applied the wrist-to-WB dose methodology as recommended in OTIB-0087 for an EE who worked at the Pantex Plant and had potentially handled Pu-238. SC&A found that NIOSH correctly applied the recommendations in OTIB-0087 to that DR. However, the exposure conditions at the Pantex Plant were not analyzed in the DR report to indicate that they were similar to those at Mound to justify applying OTIB-0087 to Pantex.

3.2 SC&A's evaluation of tables 5-1 and 5-2 and figures 5-1 and 5-2 of OTIB-0087

The gamma-ray energies listed in table 3-1 of OTIB-0087 were obtained from "Gamma Shielding Requirements for Plutonium-238 and Polonium-210" (Foster, 1966), and the neutron energy spectra in figure 3-1 of OTIB-0087 were obtained from "Neutron Flux, Spectrum, and Dose Equivalent Measurements for a 4500-W(th) $^{238}PuO_2$ General Purpose Heat Source" (Anderson, 1985). These are typical for Pu-238 and reasonable to assume for dosimetry for the Mound extremity monitoring in OTIB-0087. SC&A analyzed the data in tables 5-1 and 5-2 of OTIB-0087 and compared them to the original Mound data (Bigler, 1973, PDF pp. 177–183; Bigler & Phillabaum, 1973, PDF pp. 203–206). SC&A found that the original Mound data were correctly entered in tables 5-1 and 5-2. However, SC&A did have the following two observations.

Observation 1: Two entries from Mound data not located in OTIB-0087

SC&A found that NIOSH incorporated all six entries of the Mound data for finger-wrist-to-WB exposure (Bigler & Phillabaum, 1973, PDF p. 205) into table 5-2 of OTIB-0087. Additionally, SC&A found that NIOSH incorporated the first four entries of the Mound data for finger-wrist-to-WB exposure into table 5-1. However, SC&A could not locate where NIOSH incorporated the last two entries of the Mound data for finger-wrist-to-WB exposure into table 5-1. The wrist-to-WB ratio values for these two entries were very similar to the other wrist-to-WB ratio values in table 5-1; therefore, this would not greatly affect the results. However, it would be helpful for NIOSH to clarify why these last two entries appear to be omitted from table 5-1 of OTIB-0087.

Observation 2: Discrepancies in number of ratios between table 5-1 and figures 5-1 and 5-2

There appear to be discrepancies between the data reported in table 5-1 and figures 5-1 and 5-2. For instance, figure 5-1 reports that there were 55 values used to construct the histogram and fit the Weibull curve. However, there are only 45 valid wrist-WB gamma ratios reported in table 5-1. The mean ratio is reported as 2.116 in figure 5-1, but the mean of the wrist-WB gamma ratios in table 5-1 is 2.143.

Figure 5-2 reports that there were 53 values used to construct the histogram and fit the lognormal distribution. However, there are only 43 valid wrist-WB neutron ratios in table 5-1. Figure 5-2 also lists minimum and mean values of 0.179 and 2.551, respectively. The minimum wrist-WB neutron ratio listed in table 5-1 is 0.27, and the mean wrist-WB neutron ratio in the table is 2.502.

SC&A could not locate anything in OTIB-0087 that would explain the noted discrepancies.

3.3 SC&A's statistical analysis

The sparsity and variation of the data in table 5-1 suggests that the estimated ratios in OTIB-0087 are likely quite imprecise. Thus, extremity dose estimates based on these ratios will be imprecise. An important step in validating the estimated distribution parameters and average ratio values in OTIB-0087 would be to estimate the precision of the statistics used in the analysis.

There are several issues that suggest the estimated ratios are imprecise:

1. **Sparsity of data –** A relatively small number of observations are used in the estimation; there is a total of 28 employee observations in table 5-1. From those, there are 45 valid wrist-WB gamma ratios and 43 valid wrist-WB neutron ratios. It should be noted that those observations are also interrelated because each employee potentially supplied two wrist-WB gamma and two wrist-WB neutron observations. This reduces the effective sample size to something less than 45 and 43, respectively.

2. **Outliers –** Some large outliers in the ratio measurements affect the ability to accurately fit empirical distributions.

3. **Linear relationship –** The use of ratios to estimate wrist doses from WB doses assumes a linear relationship between the two types of doses. The linear relationship is not entirely evident from the data in table 5-1.

4. **Operation type –** There are indications that the relationship between wrist doses and WB doses differs by operation type, which suggests the need for different estimated ratios by operation type for imputations to be valid.

It would be instructive to address these items that may contribute to imprecisions of the derived ratios. SC&A provides further analysis of the data related to these items in attachment A of this report. As a result of this analysis, SC&A had the following finding about the ratio values.

Finding 2: Use of upper bound may be more appropriate in dose reconstruction

Considering the issues with the data as summarized in this section and analyzed in attachment A, SC&A suggests that it would be more claimant favorable to use an upper bound ratio, such as the upper limit of the confidence interval, instead of a distribution or average ratio value.

3.4 SC&A's evaluation of NIOSH's recommendations

Section 6.0 of OTIB-0087 recommends that when a worker was exposed to Pu-238 and an extremity dose is needed, the dose reconstructor should use the following dose ratios and dose distributions to calculate the extremity dose:

- To determine the gamma dose to the wrist, the dose reconstructor should use the Weibull distribution, shape of the curve equal to 1.3295, scale equal to 1.9271, and location equal to 0.3436, in conjunction with the gamma WB dose to determine the wrist dose.

- To determine the neutron dose to the wrist, the dose reconstructor should use the lognormal distribution, with a geometric mean of 1.5796 and a geometric standard deviation of 2.5414, in conjunction with the neutron WB dose to determine the wrist dose.

- When evaluating the finger-to-wrist extremity dose, use the average value of 3.18 times the wrist dose for the left finger dose and 2.76 times the wrist dose for the right finger. Since a meaningful fit could not be determined, assign data using a normal distribution. If it is not known if the worker was right or left-handed, use the greater of the ratios, 3.18.

SC&A's evaluation of the data presented in OTIB-0087 and related documents finds that the recommendations in section 6.0 of OTIB-0087 may be useful for DR purposes, but the recommended ratio values are imprecise as discussed in previous sections of this report and summarized in finding 2.

4 Conclusions

SC&A evaluated the original recorded Mound data, its use in constructing tables 5-1 and 5-2, and the DR recommendations. SC&A also performed a statistical analysis of the recorded data. SC&A identified two findings and two observations:

- **Finding 1:** Caution when applying ratios to other operating periods or DOE sites
- **Finding 2:** Use of upper bound may be more appropriate in dose reconstruction
- **Observation 1:** Two entries from Mound data not located in OTIB-0087
- **Observation 2:** Discrepancies in number of ratios between table 5-1 and figures 5-1 and 5-2.

5 References

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National Institute for Occupational Safety and Health. (2018). *Applications of regression in external dose reconstruction* (ORAUT-RPRT-0087, rev. 00).

Attachment A: Summary of SC&A's Statistical Analysis

SC&A analyzed the four issues referred to in section 3.3 of this report that may contribute to imprecisions of the derived ratios: (1) sparsity of data, (2) outliers, (3) linear relationship, and (4) operation type. This attachment summarizes SC&A's analysis and conclusions.

Sparsity of Data

It is understandable that there are not a lot of data to base practical procedures for imputing unmeasured doses at one bodily area from another. Unfortunately, with the small amount of data in table 5-1 of OTIB-0087, it is difficult to robustly determine a valid statistical distribution that resembles the true wrist-to-WB ratios that apply to all Pu-238 handlers. Additionally, even if the distributions could be adequately determined, fitting a statistical distribution that requires the estimation of several parameters is problematic. The parameter estimates are going to be imprecise, and data that do not fit well into the assumed distribution (outliers) compound the problem.

Outliers

Related to the issue of the lack of data is the issue of outliers in the data. If we examine the left wrist neutron doses versus WB neutron doses from table 5-1 in the form of a scatterplot (figure A-1), a couple of things stand out. The first is that there are some points that are fit very poorly by the linear model, the basis of the ratio method. In particular, the two points in the upper left quadrant of the figure are far removed from the trendline. These points have an undue influence on the parameter estimates of the line; thus, they have the same undue influence on the ratios calculated by fitting a statistical distribution to the data.

The second thing that stands out is the strength of the linear relationship between the left wrist and WB doses: The R^2 value (0.40) for this trendline, on which the estimated left wrist-WB ratio is based on, is not very large.

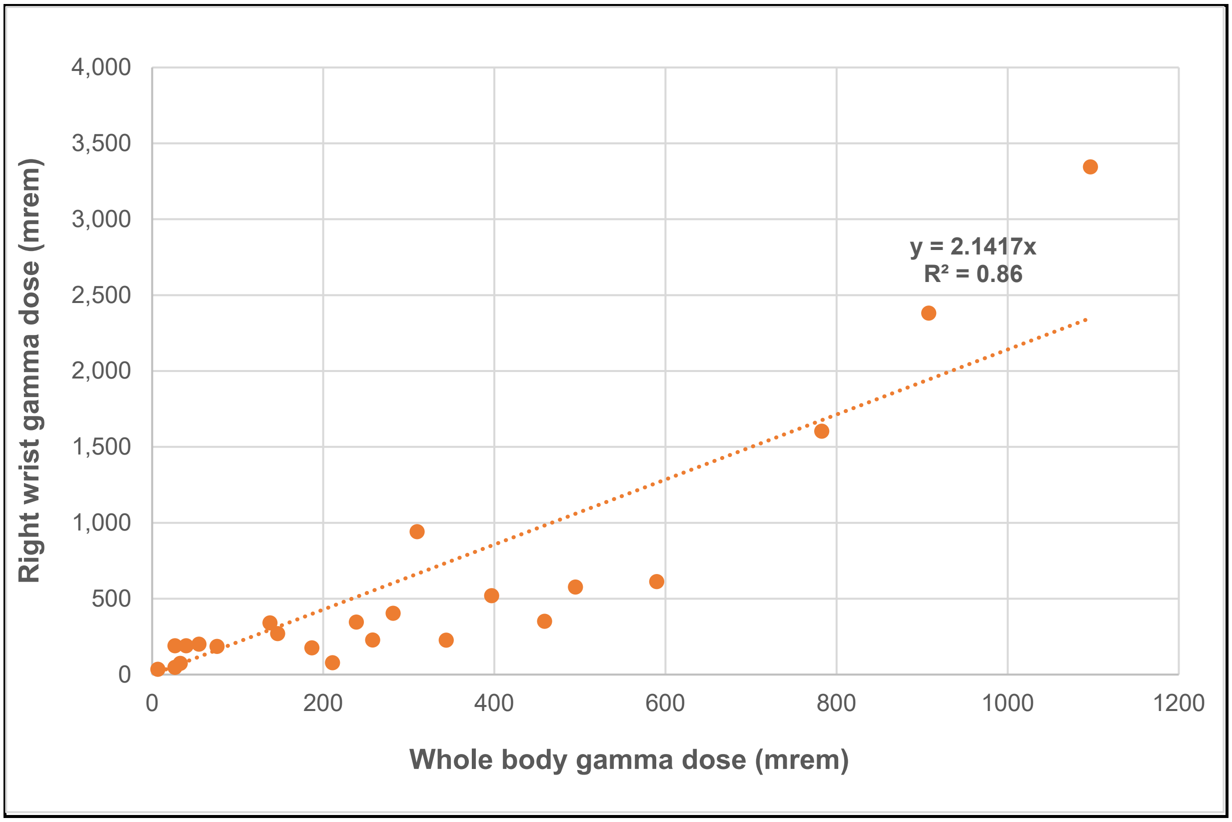
Figure A-1. Scatterplot of left wrist versus whole body neutron dose

Source: Table 5-1 of OTIB-0087 (NIOSH, 2017).

Linear Relationships Are Not Necessarily Optimal

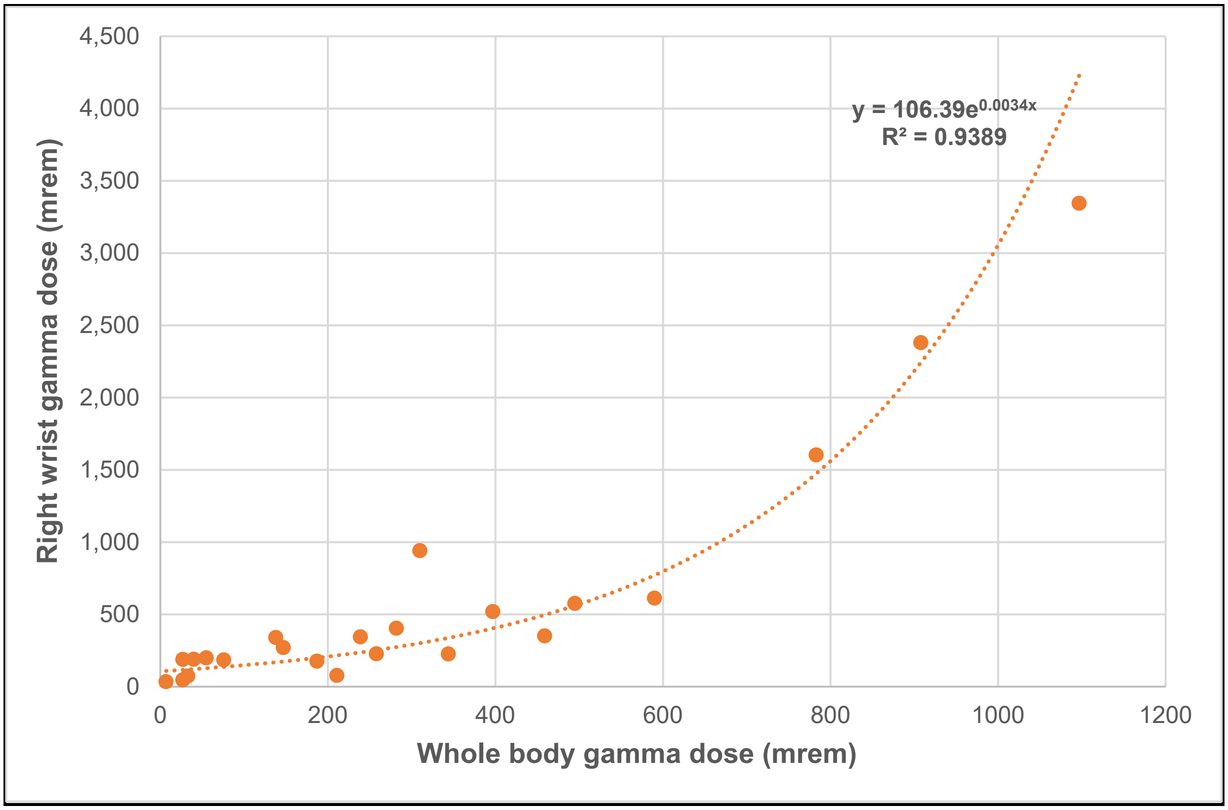
It may not be optimal to use simple ratio adjustments to impute for missing dose data. Relationships between doses at different areas of the body may be more complex than a simple ratio. For instance, a ratio connotes that there is a linear relationship between doses from two bodily areas that remains the same across individuals. However, even the limited data of this study indicate that such a relationship is not necessarily the best way to describe the association. For example, figure A-2 shows the right-wrist gamma dose measurements against the WB gamma dose measurements for all individuals that had both measurements in table 5-1 of OTIB-0087. While the linear relationship between the two measurements is strong, there is greater evidence of a nonlinear relationship. The trendline in figure A-3 models an exponential relationship between the two. The practical importance of this is that predictions of right-wrist doses from WB doses on a case-by-case basis are going to be better with a model, such as using an exponential relationship, instead of a simple ratio. However, because of the sparsity of data, the most conversative method is to use a bounding approach as indicated in finding 2 for both the right and left hand-to-WB ratios.

Figure A-2. Right wrist versus WB gamma dose – linear trendline



Source: Table 5-1 of OTIB-0087 (NIOSH, 2017).

Figure A-3. Right wrist versus WB gamma dose – exponential trendline



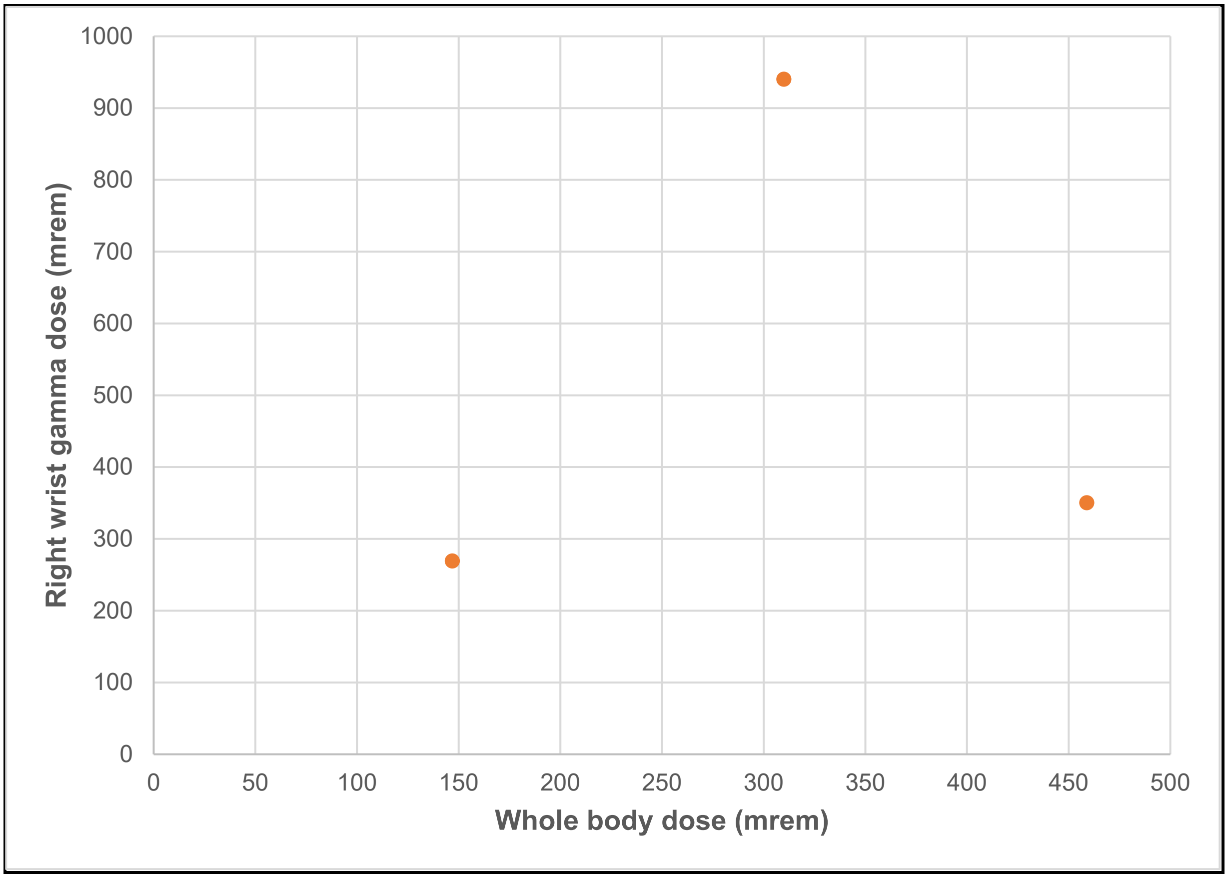
Source: Table 5-1 of OTIB-0087 (NIOSH, 2017).

Operation Type

One complexity that would be difficult to account for with simple ratios is dosage relationships that differ by type of operation. It's difficult to tell from such a sparse data set, but looking at the measurements from the four employees involved in metallurgical evaluations gives a different picture than that obtained from the entire dataset. Figures A-4 and A-5 display the right wrist versus WB and left wrist versus WB gamma doses measured for the employees involved in metallurgical evaluations. (Note: Only two of the employees registered left wrist measurements and three registered right wrist measurements.) These graphs suggest a relationship different than the overall relationship shown in figure A-2.

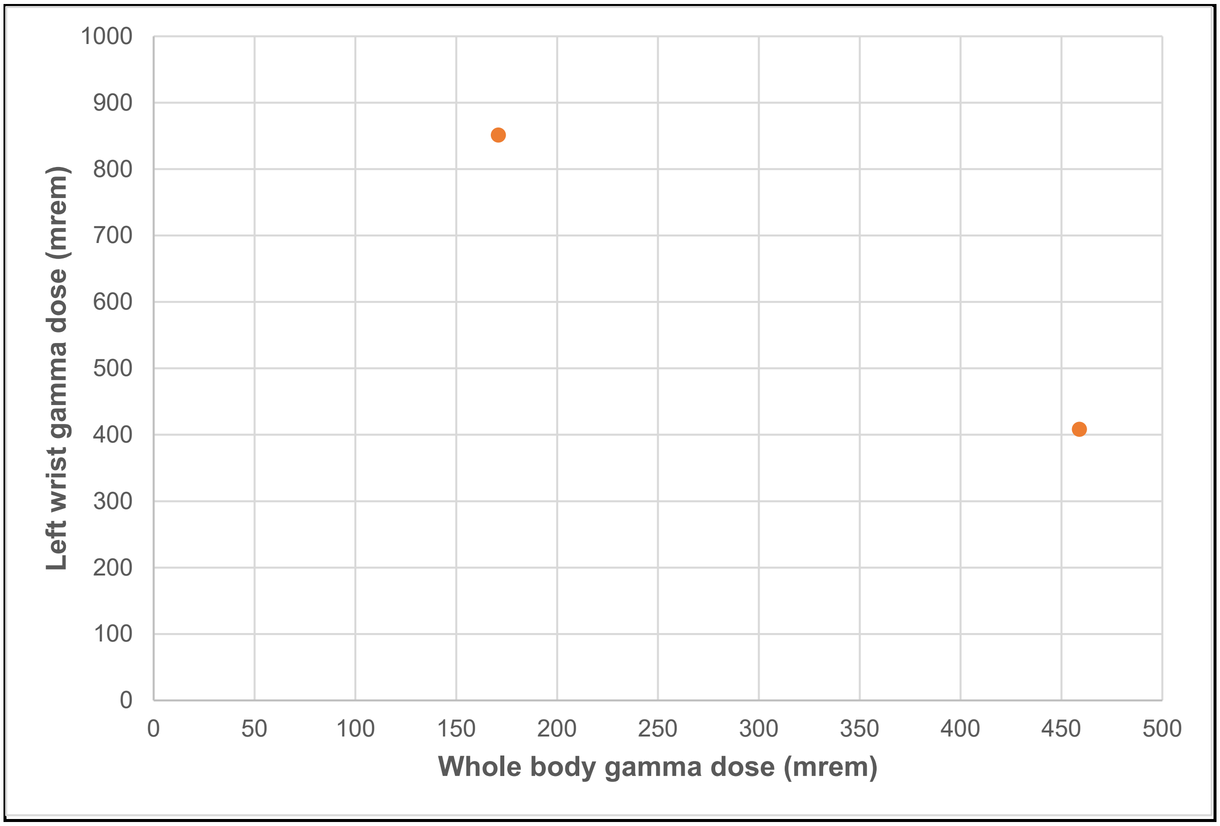
This is partly a problem with using the small data set and partly a potential issue due to complexity. The small data set does not allow us to fully grasp the differences between types of operations, but it does indicate the possibility that the ratios for metallurgical evaluations are different from those of other operations.

Figure A-4. Right wrist versus WB gamma dose – metallurgical evaluations



Source: Table 5-1 of OTIB-0087 (NIOSH, 2017).

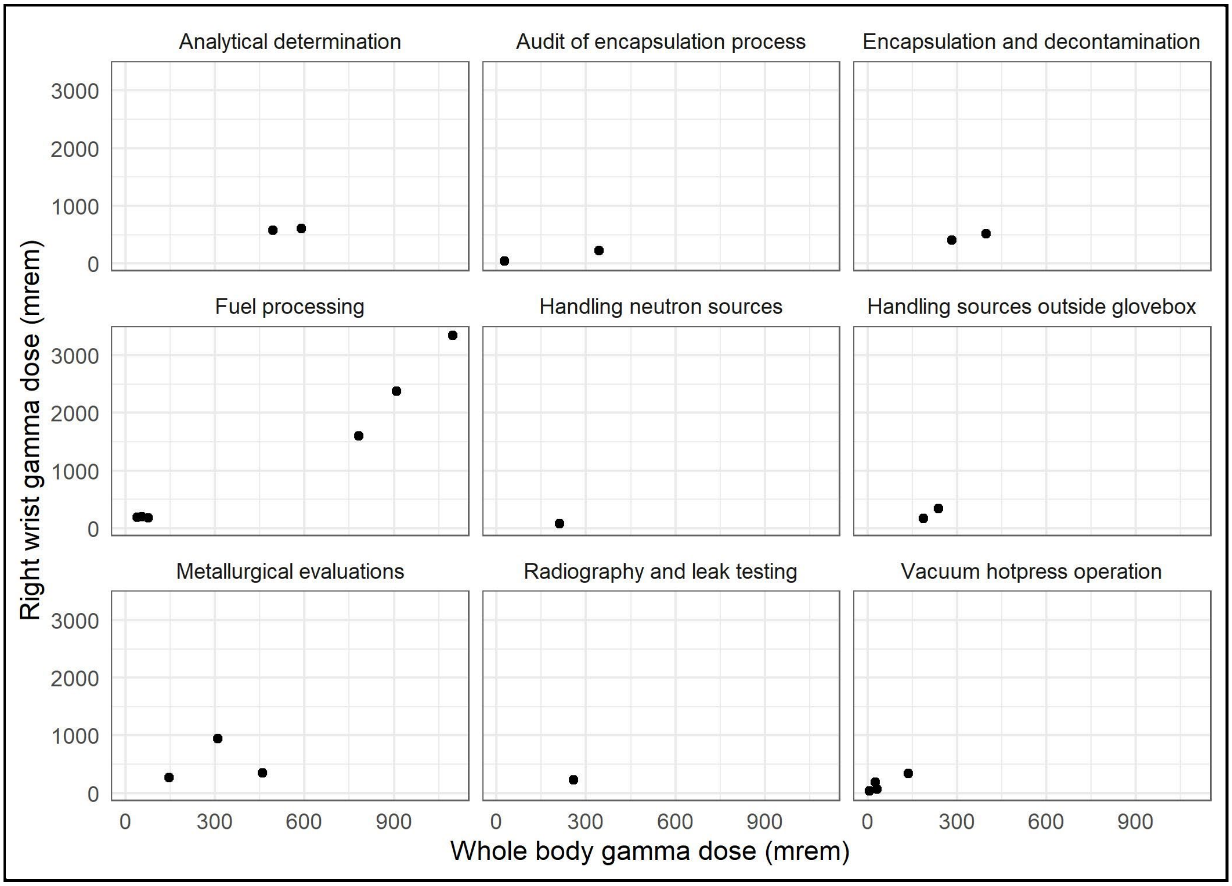
Figure A-5. Left wrist versus WB gamma dose – metallurgical evaluations



Source: Table 5-1 of OTIB-0087 (NIOSH, 2017).

Another way to think about this is to graph right wrist dosage by WB dosage for each operation type side by side, as in figure A-6. In this figure, each pane in the figure displays the right-wrist-by-WB gamma dosage for a different operation type. It is clear from this graph that the fuel processing (FP) data drive the linear relationship observed in the overall graph (figure A-2). If we removed the FP data from the analysis, we would get a very different picture of the distribution of right-wrist-to-WB gamma ratios and a very different estimated ratio for right-wrist-to-WB gamma doses.

Figure A-6. Right wrist versus WB gamma dose by operation type



Source: Table 5-1 of OTIB-0087 (NIOSH, 2017).

Other and Similar Work

SC&A noted that the quantile regression work in ORAUT-RPRT-0087, revision 00, "Application of Regression in External Dose Reconstruction" (NIOSH, 2018), modeled the components of ratio relationships differently. One dose was used to predict for the other in a more complex way. While the basis of the relationship was still linear in that work, a parametric distribution was not overlaid on the relationship. Additionally, and importantly, the predicted relationship was allowed to vary at different quantiles of the distribution. These are two concepts that might be effectively exploited in an extension of OTIB-0087 for modeling extremity doses in relationship to WB doses, if there were adequate data to support the model.