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ADVISORY BOARD ON
RADIATION AND WORKER HEALTH

National Institute for Occupational Safety and Health

SC&A'S EVALUATION OF ORAUT-OTIB-0045, REVISION 01, "HISTORICAL EVALUATION OF THE FILM BADGE DOSIMETRY PROGRAM AT THE Y-12 PLANT IN OAK RIDGE, TENNESSEE: PART 2 – NEUTRON RADIATION"

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ABBREVIATIONS AND ACRONYMS

ABRWH	Advisory Board on Radiation and Worker Health
CF	correction factor
D-D	deuterium-deuterium
DE	dose equivalent
DR	dose reconstruction
eV	electron volt
GM	geometric mean
GSD	geometric standard deviation
MDL	minimum detection level
MeV	mega-electron volt
ML	maximum likelihood
mrem	millirem
n/p	neutron-to-photon ratio
NIOSH	National Institute for Occupational Safety and Health
NTA	nuclear track emulsion, Type A
ORAUT	Oak Ridge Associated Universities Team
OTIB	ORAUT technical information bulletin
Q-Q	quantile-quantile
UF_4	uranium tetrafluoride
UO_3	uranium trioxide
Y-12	National Security Complex

1.0 INTRODUCTION AND BACKGROUND

As a result of tasking on December 3, 2018, after the Subcommittee for Procedure Reviews meeting of October 31, 2018, SC&A has performed a technical review of ORAUT-OTIB-0045, Revision 01, *Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Plant in Oak Ridge, Tennessee: Part 2 – Neutron Radiation*, issued November 30, 2009 (NIOSH 2009, referred to as "OTIB-0045"). The purpose of OTIB-0045 is to provide information about the National Security Complex (Y-12) film badge dosimetry used for the monitoring of neutron radiation. Three other Y-12 reports have been issued addressing gamma and beta dosimetry and external coworker doses:

- ORAUT-OTIB-0044, *Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Facility in Oak Ridge, Tennessee: Part 1 – Gamma Radiation*, Revision 01, issued April 29, 2013 (NIOSH 2013a)
- ORAUT-OTIB-0046, *Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Plant in Oak Ridge, Tennessee: Part 3 – Beta Radiation*, Revision 00, issued June 22, 2007 (NIOSH 2007)
- ORAUT-OTIB-0064, *Coworker External Dosimetry Data for the Y-12 National Security Complex*, Revision 02, issued April 29, 2013 (NIOSH 2013b). In ORAUT-OTIB-0064, the National Institute for Occupational Safety and Health (NIOSH) used external gamma dose data from ORAUT-OTIB-0044 and external beta dose data from ORAUT-OTIB-0046 to derive the 50th and 95th percentile coworker gamma and beta doses for the period 1947–1979 for use in dose reconstruction (DR).

This report presents SC&A's evaluation of the statistical method, technical analyses, and documentation in OTIB-0045 for using neutron dose records to derive neutron-to-photon ratio (n/p) values at Y-12 for the period 1950 to 1980, during the period when nuclear track emulsion, Type A (NTA) film was used for neutron dosimetry.

2.0 OVERVIEW OF ORAUT-OTIB-0045

The following is a brief overview of OTIB-0045.

- **Neutron Film Badge Dosimetry at Y-12 –** NTA film was used to monitor neutron exposure at Y-12 from approximately 1950 to 1980.

- **Major Sources of Neutrons at Y-12 –** The major sources of neutrons at Y-12 during the NTA film monitoring era were:

  – **86-inch Cyclotron –** This accelerator operated from 1950 through 1961 and accelerated protons to a maximum energy of approximately 20 mega-electron volts (MeV).

  – **Encapsulated Neutron Sources** – Many neutron sources using the alpha-neutron reaction were used at Y-12 during the NTA film badge era. These included plutonium-beryllium, radium-beryllium, americium-lithium, and americium-beryllium, plus neutron-emitting californium-252.

- **Chemical Operations Areas –** Y-12 processed natural and enriched uranium from approximately 1949 to 1964. At high enrichments (i.e., greater than 95%), the neutron exposure can be as high as 2 millirem (mrem) per hour at 3 feet from a storage container, with an n/p value of 2.

- **D-D Project** – The acceleration of deuteron ions onto a deuteron target to create neutrons was used in research at Y-12 during 1949–1950 and was termed the D-D Project. The D-D reaction creates monoenergetic neutrons of 2.5 MeV. The neutron dosimetry used during this time appears to be inadequate and was not included in the database used in OTIB-0045.

- **Neutron Dose Records for Y-12 –** The neutron dose data available for use in deriving Y-12 n/p values in OTIB-0045 were records from approximately 17,000 Y-12 workers for the period 1950 through 1980. In the 17,000 records, there were 143 workers who had 375 positive neutron doses recorded.

- **Statistical Method** – NIOSH used the maximum likelihood (ML) statistical method to analyze the available neutron dose data to derive the recommended n/p values in OTIB-0045.

- **Evaluation of Film Badge Data** – NIOSH evaluated quarterly neutron dose records and summarized them in OTIB-0045 in the following tables:

  - **Table 6-1 –** This table lists the quarterly neutron doses and cumulative neutron dose by year from 1952 to 1962.

  - **Table 6-2 –** This table lists the cumulative neutron dose by department and year from 1952 to 1962.

- **Neutron-to-Gamma Dose Ratios –** The available data from the 143 workers with 375 recorded positive neutron doses were analyzed in OTIB-0045 using the ML statistical method. Of the 25 departments with positive neutron doses recorded, only four departments had sufficient neutron dose data to warrant the derivation of individual departmental n/p values. The four departments were:

  - Health Physics, Department 2108
  - Alloy Maintenance, Department 2159
  - Material Engineering, Department 2160
  - Developmental Operations, Department 2301

  The remaining departments were assigned an n/p value resulting from the analysis of all dose data from all departments with positive recorded neutron doses, except the dose data from the Product Chemical and Product Processing Departments, which were not used in deriving the n/p value because of abnormalities found in that data, as discussed in Section 3.2.2 of this report.

The following figures in OTIB-0045 present the results of the analysis of the positive neutron dose data as lognormal quantile-quantile (Q-Q) plots:

- **Figure 6-1 –** This figure shows the lognormal Q-Q plot of neutron doses from all Y-12 departments.
- **Figure 6-2 –** This figure shows the lognormal Q-Q plot of neutron-to-gamma dose ratios for the Health Physics Department (2108).
- **Figure 6-3 –** This figure shows the lognormal Q-Q plot of neutron-to-gamma dose ratios for the Alloy Maintenance Department (2159).
- **Figure 6-4 –** This figure shows the lognormal Q-Q plot of neutron-to-gamma dose ratios for the Material Engineering Department (2160).
- **Figure 6-5 –** This figure shows the lognormal Q-Q plot of neutron-to-gamma dose ratios for Developmental Operations Department (2301).
- **Figure 6-6 –** This figure shows the lognormal Q-Q plot of neutron-to-gamma dose ratios for all Y-12 departments.
- **Figure 6-7 –** This figure shows the lognormal Q-Q plot of neutron-to-gamma dose ratios for all Y-12 departments other than the Product Chemical Department (2616) and the Product Processing Department (2617).

- **Assignment of Neutron Dose –** Table 7-1 of OTIB-0045 presents the final results of the analysis of the neutron dose data used to derive recommended n/p values for Y-12 during the NTA film monitoring era. Table 7-1 provides the recommended n/p values, along with their geometric mean (GM), geometric standard deviation (GSD), and expected n/p value for four individual departments, Health Physics (2108), Alloy Maintenance (2159), Material Engineering (2160), Developmental Operation (2301), and default values for all other departments.

- **Attachment A –** This attachment consist of two tables:

  - **Table A-1 –** This table contains quarterly neutron and gamma dose data, and resulting n/p values, by worker, for the 143 Y-12 workers with positive neutron doses recorded during the years 1952 through 1962. There were a total of 375 positive neutron doses recorded.

  - **Table A-2 –** This table contains quarterly neutron and gamma dose data, and resulting n/p values, by department, for 143 Y-12 workers with positive neutron doses recorded during the years 1952 through 1962. There were a total of 375 positive neutron doses recorded.

- **Attachment B –** This attachment contains Table B-1, which lists the rounded quarterly neutron dose values for Y-12 workers as a function of Y-12 department for the film badge period from 1950 to 1980 (Markowitz et al. 2004, Appendix B1, PDF page 158). There are a total 143 Y-12 workers with positive neutron doses during the years 1952 through 1980. A total of 376 positive neutron doses were recorded, which is one more than contained in the database used by NIOSH in OTIB-0045.

3.0 SC&A'S EVALUATION OF ORAUT-OTIB-0045

The following is a summary of SC&A's evaluation of the statistical method, technical analyses, and documentation used in OTIB-0045.

3.1 SC&A'S EVALUATION OF THE STATISTICAL METHOD USED IN ORAUT-OTIB-0045

SC&A concurs with the use of the ML statistical analysis of the Y-12 neutron data for deriving n/p values for DR purposes. Similar ML statistical analysis were used in ORAUT-OTIB-0044 (NIOSH 2013a), which SC&A reviewed and concurred with the ML statistical method employed (SC&A 2017, page 8). SC&A had no findings about the statistical method but did have one observation:

Observation 1. Inconsistency in GSD Values – The n/p GM values listed in OTIB-0045, Table 7-1, are the same as the respective n/p GM values contained in the Q-Q plots in Figures 6-2 through 6-5 and 6-7. However, the n/p GSD values in Table 7-1 are all slightly higher than the respective values contained in the Q-Q plots in Figures 6-2 through 6-5 and 6-7.

3.2 SC&A'S EVALUATION OF TECHNICAL ANALYSES USED IN ORAUT-OTIB-0045

SC&A evaluated NIOSH's technical analyses of the recorded neutron dose data in Section 3.0 of OTIB-0045, from which n/p values were derived in Section 6.0. The following is a summary of SC&A's evaluation.

3.2.1 Neutron Energy Fields and NTA Film Response

The major Y-12 sources of neutrons, their associated energy fields, and NTA film response during the film badge era were as follows.

86-inch Cyclotron

This accelerator operated from 1950 through 1961 and accelerated protons to a maximum energy of approximately 20 MeV; therefore, the maximum neutron energy would have been around 20 MeV. Outside the accelerator shielding, where workers may have been exposed, the neutron energies would have been moderated and a continuous energy spectra from thermal (0.025 electron volts [eV]) up to the maximum energy of 20 MeV could have been present. The magnitude of the neutron flux around a proton accelerator decreases exponentially as the energy increases (Patterson and Thomas 1973, page 467), and the dose equivalent (DE) increases as a function of increasing neutron energy (Patterson and Thomas 1973, page 77). This combination results in the majority of the neutron DE being from neutrons in the 0.1 MeV to 14 MeV range. Therefore, SC&A concurs with the recommendation in OTIB-0045, Table 3-2, page 14, that the neutron DE fraction of 0.46 for 0.1–2 MeV neutrons and 0.54 for 2–20 MeV neutrons be used for exposure to neutron fields at the Y-12 86-inch cyclotron. Additionally, SC&A concurs that

30% of the neutron DE was below the 0.7 MeV threshold of NTA film (correction factor of 1/(1.0 − 0.30) = 1.4). SC&A also concurs with the use of an angular dependence factor of 1.3 (NIOSH 2006, Table 8-1, page 18). This results in a total correction factor of 1.4 × 1.3 = 1.8 for neutron doses recorded at the 86-inch cyclotron; this value agrees with the total correction factor of 1.8 recommended in NIOSH 2006, Table 8-1.

Encapsulated Neutron Sources

Various neutron sources using the alpha-neutron reaction were used at Y-12 during the NTA film badge era. These included plutonium-beryllium, radium-beryllium, americium-lithium, and americium-beryllium, plus neutron-emitting californium-252. Alpha-neutron sources generally produce neutron energy spectra in the 0.025 eV to 10 MeV range, with the most predominate neutron energies centered on 4 MeV (Patterson and Thomas 1973, page 76), resulting in the majority of the neutron DE being from 0.1 MeV to 10 MeV neutrons. Californium-252 emits neutrons centered on 2 MeV. Therefore, SC&A concurs with the recommendation in OTIB-0045, Table 3-4, page 17, that the neutron DE fraction of 0.57 for 0.1–2 MeV neutrons and 0.43 for 2–20 MeV neutrons be used for exposure to neutron fields from encapsulated neutron sources. SC&A also concurs with the use of an angular dependence factor of 1.3 (NIOSH 2006, Table 8-1). However, SC&A did have the following finding:

Finding 1. Inconsistency in NTA Threshold Missed Fraction for Shielded Encapsulated Sources - SC&A found that the recommendation in OTIB-0045, page 16, to assume that 40% of the neutron DE falls below the 0.7 MeV threshold of NTA film (correction factor of 1/(1.0 − 0.40) = 1.7) does not agree with the recommendation in ORAUT-OTIB-0051, Revision 00, *Effect of Threshold Energy and Angular Response of NTA Film on Missed Dose at the Oak Ridge Y-12 Facility* (NIOSH 2006, page 17, referred to as "OTIB-0051"):

> *These missed dose values are as follows:…51% for the shielded radionuclide sources at the Health Physics Calibration Laboratory*

Additionally, Table 8-1 of OTIB-0051, page 18, lists a missed neutron fraction of 2.0, with a recommended total correction factor of 2.7.

Using a factor of 51% would result in a total correction factor of 1/(1 − 0.51) × 1.3 = 2.0 × 1.3 = 2.7 (NIOSH 2006, Table 8-1) instead of 2.2 as recommended in OTIB-0045, page 16, for recorded neutron doses from encapsulated neutron sources. Although the use of the recommended threshold correction factor of 1.7 is claimant favorable for unshielded radionuclide and californium neutron sources, it is not for shielded neutron sources where the energy spectra is degraded and more neutrons fall below the NTA threshold. It does not appear to be consistent with the value recommended in OTIB-0051.

Chemical Operations Areas

Y-12 processed natural and enriched uranium from approximately 1949 to 1964. At high enrichments, i.e., greater than 95%, the neutron exposure can be as high as 2 mrem per hour at 3 feet from a storage container, with an n/p value of 2. The neutron energy spectra at such facilities would be relatively low in neutron energy. Therefore, more of the neutrons would fall below the NTA film threshold compared to sources with higher-energy neutron spectra, such as around a high-energy particle accelerator. This results in the need for a larger threshold dependence factor and assignment of dose as 100% 0.1–2.0 MeV neutrons. Therefore, SC&A concurs with the recommendation in OTIB-0045, Table 3-5, page 18, that the neutron DE fraction of 1.00 for 0.1–2 MeV neutrons be used for exposure to neutron fields from chemical operations areas. SC&A also concurs with the use of an angular dependence factor of 1.3 (NIOSH 2006, Table 8-1). However, SC&A did have the following finding:

Finding 2. Inconsistency in NTA Threshold Missed Fraction for Chemical Operations Areas – SC&A found that the recommendation in OTIB-0045, page 18, to assume that 40% of the neutron DE falls below the 0.7 MeV threshold of NTA film (correction factor of $1/(1.0 - 0.40) = 1.7$) does not agree with the recommendation in OTIB-0051, page 17:

> *These missed dose values are as follows:…54% for the highly enriched UF_4 and UO_3 storage containers.*

Additionally, Table 8-1 of OTIB-0051 lists a missed neutron fraction of 2.2, with a recommended total correction factor of 2.9.

Using a factor of 54% would result in a total correction factor from enriched uranium storage containers of $1/(1 - 0.54) \times 1.3 = 2.2 \times 1.3 = 2.9$ (NIOSH 2006, Table 8-1) instead of 2.2 as recommended in OTIB-0045, page 18, for chemical operation areas, which was based on measurements of containers of uranium tetrafluoride (UF_4) and uranium trioxide (UO_3) in storage, as outlined on pages 17 - 18 of OTIB-0045.

While SC&A finds the threshold correction factor of 1.7 plausible for the chemical operation areas, it does not appear to be consistent with the value of 2.2 recommended in OTIB-0051.

Summary of Total Correction Factor: OTIB-0045 versus OTIB-0051

Table 1 summarizes the recommended value of the energy threshold correction factor and the total correction factor, as a function of neutron source in OTIB-0045 compared to OTIB-0051. In both OTIB-0045 and OTIB-0051, an angular response correction factor of 1.3 was used.

Table 1. Summary of Recommended Threshold and Total Correction Factor

Neutron Source	OTIB-0045 Threshold CF (page)	OTIB-51 Threshold CF Table 8-1, p. 18	OTIB-0045 Total CF (page)	OTIB-51 Total CF Table 8-1, p. 18	Agreement?
Unshielded radionuclide sources	None	1.0	None	1.3	Not applicable
Californium-252 sources	1.3 (p.16)	1.3	1.7 (p.16)	1.7	Yes
86-inch cyclotron	1.4 (p.14)	1.4	1.8 (p.14)	1.8	Yes
Shielded radionuclide sources	1.7 (p.16)	2.0	2.2 (p.16)	2.7	No
Enriched uranium storage	1.7 (p.18)	2.2	2.2 (p.18)	2.9	No

Note. CF = correction factor.

3.2.2 Deriving Neutron-to-Photon Ratio Values

OTIB-0045, Section 6.0, analyzed the available data from the 143 workers with 375 recorded positive neutron doses using the ML statistical method. Of the 25 departments with positive neutron doses recorded, only four departments had sufficient neutron-dose data to warrant the derivation of individual departmental n/p values. The results of the analysis are summarized in OTIB-0045 Tables 6-1, 6-2, and 7-1 and in Figures 6-1 to 6-5.

In analyzing the neutron dose data for deriving n/p values, OTIB-0045 states in Section 6.2 (pages 22 and 25):

> *Figure 6-6 shows the neutron-to-gamma ratio based on the combined data for all 25 departments. The neutron-to-gamma ratio for* ***all*** *departments combined appears to be unreasonably large in comparison with the ratios for the four specific departments in Figures 6-2 to 6-5. It was determined that the unacceptably large value was due primarily to* ***two departments, the Product Chemical Department (2616) and the Product Processing Department (2617).*** *Departments 2616 and 2617 have data for 32 workers, but their positive neutron doses occurred mainly in 1954 and 1955 and…include 25 quarterly neutron doses that are multiples of 50 mrem. These positive neutron doses are likely to have consisted of assigned biweekly doses of 50 mrem substituted for below-MDL readings.* [Emphases added.]

OTIB-0045 explains that the analysis was then rerun using the neutron dose data for all department, excluding the data from the Product Chemical and the Product Process Departments, to obtain the plot shown in Figure 6-7, and to construct Table 7-1.

SC&A reviewed the Product Chemical and the Product Process Departments neutron dose data on pages 54–55 of OTIB-0045 to determine if it was technically reasonable to eliminate the Product Chemical and the Product Process Departments data. Analyzing the data indicated:

- **Product Chemical –** 9 out of 11 neutron doses of ≥100 mrem had zero recorded gamma dose (82%).
- **Product Processing –** 20 out of 32 neutron doses of ≥100 mrem had zero recorded gamma dose (63%).

If the neutron dose reading was ≥100 mrem, and the gamma dose reading was less than the minimum detection level (MDL) of 30 mrem (and therefore recorded as zero), this would indicate an n/p value of >3. It would be unusual to consistently have neutron fields with n/p values of >3 for chemical processing and handling of natural and enriched uranium at Y-12. Therefore, SC&A finds it reasonable to exclude the Product Chemical and the Product Process Departments neutron dose data on the basis of this technical assessment.

OTIB-0045 did include the Maintenance Shops (Department 2003) neutron dose data on page 47 in Table A-2, which contain two recorded neutron doses >100 mrem with gamma dose recorded as zero. It is possible that this department's data should have also been excluded; however, two data points out of 375 would not have had a significant effect on the overall n/p value recommended, and including them was very slightly claimant favorable.

SC&A evaluated NIOSH's analyses of the recorded neutron dose data, and the derived n/p values, and concurs with the results and had no findings in this section. However, SC&A did identify several area that would benefit from further discussion or clarification:

Observation 2. Clarification Needed Concerning Application of Gamma Minimum Detection Level – The second paragraph of Section 6.2, page 22, of OTIB-0045 states:

> *Only* ***four of the 25 departments*** *had sufficient positive neutron dose data to calculate a departmental neutron-to-gamma dose ratio. These four departments are Health Physics (2108), Alloy Maintenance (2159), Material Engineering (2160), and Developmental Operations (2301). Figures 6-1 to 6-5 present Q-Q plots for the four departments along with ML estimates for lognormal parameters and other statistical information. In these analyses,* ***if a gamma dose is zero (i.e., a nondetect), the neutron- to-gamma dose ratio is obtained by dividing the neutron dose by an MDL of 30 mrem for the quarterly gamma-ray doses*** *and treating the ratio as right censored (see Section 5 for details).* [Emphases added.]

It is not clear from this paragraph if the MDL value of 30 mrem was used when the gamma dose was reported as zero in all the analyses for all the departments, or just for the four departments previously mentioned.

3.2.3 Assigning Neutron Dose

OTIB-0045, Table 7-1, page 27, provides a convenient summary of the recommended n/p values to be used in DR, and Section 8.0 provides some summary information. However, Section 8.0 would benefit from including a defined time period for which the n/p values recommended in Table 7-1 are to be applied.

Observation 3. Definite Time Period Needs to Be Stated for Use of n/p Values – OTIB-0045, Section 8.0, should state the exact years the n/p values in Table 7-1 are to be applied to provide for consistency in DR. OTIB-0045, page 6, mentions that thermoluminescent dosimetry replaced film dosimetry in 1980. Page 7 includes a statement concerning assigning NTA film badges during the period 1952 to 1961. Page 11 mentions the film badge period was from 1950 to 1980. It would be helpful if OTIB-0045 stated the exact beginning month and year and the exact ending month and year to which the n/p values in Table 7-1 are to be applied.

3.3 SC&A's Evaluation of Documentation in ORAUT-OTIB-0045

SC&A evaluated NIOSH's documentation in OTIB-0045 for deriving n/p values for Y-12 workers. SC&A found the document well written and the data presented in a logical pattern that provides useful information and guidance for DR. SC&A did find two minor reference errors:

- Page 20 – The second line of Section 5.0 contains a reference to Section 5.2 concerning four departments at Y-12; however, it appears that it should refer to Section 3.2 of OTIB-0045. This may have been a carryover from ORAUT-RPRT-0033 (NIOSH 2005).

- Page 27 – Table 7-1, Footnote b states "See Figures 6-6 to 6-9 and 7-11." It appears that this should read "See Figures 6-2 to 6-5 and 6-7."

4.0 SUMMARY AND CONCLUSIONS

Statistical Method – SC&A concurs with the use of the ML statistical analysis of the Y-12 neutron data for deriving n/p values for DR purposes. SC&A had no findings in this section, but did have one observation:

- **Observation 1. Inconsistency in GSD Values** (as described in Section 3.1 above)

Technical Analyses – SC&A evaluated NIOSH's technical analyses and recommendations in OTIB-0045 and found them to be reasonably accurate and applicable. However, SC&A did have two findings and two observations that would benefit from further discussion or clarification, as described in Section 3.2 above:

- **Finding 1. Inconsistency in NTA Threshold Missed Fraction for Shielded Encapsulated Sources**
- **Finding 2. Inconsistency in NTA Threshold Missed Fraction for Chemical Operations Areas**
- **Observation 2. Clarification Needed Concerning Application of Gamma Minimum Detection Level**
- **Observation 3. Definite Time Period Needs to Be Stated for Use of n/p Values**

Documentation – SC&A evaluated the documentation used in assigning neutron dose and found two minor reference errors on page 20 and page 27, as described in Section 3.3 above.

5.0 REFERENCES

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