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National Institute for Occupational Safety and Health

SC&A's Review of ORAUT-RPRT-0060, Revision 00, "Neutron Dose from Highly Enriched Uranium"

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Abbreviations and Acronyms

ABRWH	Advisory Board on Radiation and Worker Health
DOE	U.S. Department of Energy
DR	dose reconstruction
DU	depleted uranium
EE	energy employee
GDP	gaseous diffusion plant
HEU	highly enriched uranium
IREP	Interactive RadioEpidemiological Program
K-25	Oak Ridge Gaseous Diffusion Plant
LEU	low-enriched uranium
LOD	limit of detection
mrem	millirem
NAS	National Academy of Sciences
NIOSH	National Institute for Occupational Safety and Health
N:P	neutron-to-photon
n/p	neutron-to-photon ratio
n/s-g	neutron per second per gram
NU	natural uranium
ORAUT	Oak Ridge Associated Universities Team
PGDP	Paducah Gaseous Diffusion Plant
PORTS	Portsmouth
QR	quantile regression
QRA	quantile regression analysis
TBD	technical basis document
U	uranium
wt %	weight percent
Y-12	National Security Complex

1 Introduction and Background

On March 28, 2019, the National Institute for Occupational Safety and Health (NIOSH) issued ORAUT-RPRT-0060, revision 00, "Neutron Dose from Highly Enriched Uranium" (ORAUT, 2019; "RPRT-0060"). The purpose of RPRT-0060 was to determine reasonable neutron-to-photon (N:P) ratios that can be used to assign neutron dose from sites that handled highly enriched uranium (HEU) compounds during periods when neutron dose data were not reliable, not available, or not recorded. These sites include gaseous diffusion plants (GDPs), such as the Oak Ridge Gaseous Diffusion Plant (K-25) in Oak Ridge, Tennessee; Portsmouth (PORTS) in Piketon, Ohio; and Paducah (PGDP) in Paducah, Kentucky, and also uranium metal processing facilities such as the National Security Complex (Y-12) in Oak Ridge, Tennessee. For K-25, this time period was prior to 1992 (NIOSH, 2019, p. 2); for PORTS, this time period was prior to 1995 (NIOSH, 2019, p. 2); and for PGDP, this time period was prior to 1998 (ORAUT, 2017, p. 25). For Y-12, this time period is not specified in ORAUT-TKBS-0014-6, revision 02 (ORAUT, 2009), but page 43 indicates that while the potential for neutron exposure was confined to small areas at the Y-12 site, it is important to include neutron doses for workers for whom neutrons were a relevant source of radiation.

On June 21, 2023, the Subcommittee for Procedure Reviews tasked SC&A with reviewing RPRT-0060.

2 Outline of RPRT-0060

Section 2.0, "Background": Tables 2-1 and 2-2 of RPRT-0060 provide background material in the form of a summary of the various radiological properties of the uranium materials processed at the GDPs and Y-12. Table 2-3 of RPRT-0060 lists the dose fractions as a function of neutron energies from <10 kiloelectron volts to 20 mega-electron volts. SC&A checked the validity of the data in section 2.0 using the appropriate references provided in the text and footnotes of RPRT-0060. SC&A's evaluation of section 2.0 is outlined in section 3.2 of this review.

Section 3.0, "Neutron Dose Data from Facilities": This section provides a summary of the neutron dose data available from measured neutron doses and N:P ratios near storage cylinders containing depleted uranium (DU), natural uranium (NU), low-enriched uranium (LEU), HEU, and work area monitoring (ORAUT, 2019):

- Section 3.1.1 provides a summary of the PGDP cylinder painting and storage yard neutron and photon dose measurements, with a resulting average N:P ratio of 0.2.
- Section 3.1.2 provides information concerning neutron and photon dose measurements at PORTS near storage cylinders, vaults, and from area monitoring. Additionally, table 3-1 of RPRT-0060 summarizes the number of employees monitored for total external dose and neutron dose for 1992 through 2013. NIOSH derived an average N:P ratio of 0.369 $\pm$0.2 from the PORTS dosimetry data.
- Section 3.1.3 provides information about neutron and photon dose measurements at K-25 near cylinder storage yards, modeling studies, equipment and area monitoring surveys, and employee dosimetry measurements. Table 3-2 of RPRT-0060 presents a summary of

the K-25 annual photon/beta and neutron badge exchanges from 1989 through 2012. NIOSH derived an N:P ratio of 0.420 from the K-25 dosimetry data.

- Section 3.2 contains a discussion of Y-12 employee neutron and photon dosimetry data, which are analyzed further in section 4.0 of RPRT-0060. Additionally, the Y-12 N:P ratios derived from area survey data for 1992 through 2004 are summarized in table 3-3 of RPRT-0060. SC&A derived an average N:P ratio of 0.40 from the N:P data in table 3-3.

Section 4.0, "Additional Data Analysis of Employee Data Measurements for K-25, Portsmouth, and Y-12 Plant": This section provides additional analysis of the K-25, PORTS, and Y-12 neutron and photon dosimetry data by the quantile regression (QR) method that is recommended in ORAUT-RPRT-0087, revision 00 (ORAUT, 2018). Figures 4-1 (K-25), 4-2 (PORTS, not PGDP, as is labeled in figure 4-2), and 4-3 (Y-12) of RPRT-0060 present the analysis of the employee dosimetry neutron dose (rem) as a function of photon dose (rem) using QR, with figure 4-4 showing the results of combining the data from all three sites. Table 4-1 of RPRT-0060 summarizes the QR fit parameters for K-25, PORTS, and Y-12 employee dosimetry data measurements. Table 4-1 provides the 50th and 95th percentile N:P slope value and the neutron dose intercept value (rem) obtained from using QR fit to the dosimetry data, as illustrated in figures 4-1 through 4-4 of RPRT-0060.

Section 5.0, "Photon Summary and Conclusions": This section summarizes the N:P ratios analyzed in sections 2 through 4 of RPRT-0060. Table 5-1 of RPRT-0060 summarizes the neutron and photon dose rate measurements (millirem (mrem) per hour) and the resulting N:P ratios for K-25, PORTS, PGDP, and Y-12, along with N:P-ratio-related information recommended in the U. S. Department of Energy's (DOE's) "Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities" (DOE, 2009). Table 5-2 of RPRT-0060 summarizes the N:P ratio values obtained by the ratio method (i.e., neutron dose divided by photon dose) and the equations for the 50th and 95th percentile neutron doses derived using a QR fit of the measured neutron and photon doses for K-25, PORTS, Y-12, and their combined data.

The difference between (1) neutron dose obtained by the ratio method (i.e., the co-exposure neutron dose divided by the co-exposure photon dose times the energy employee's (EE's) measured photon dose) and (2) neutron dose calculated using an equation derived from a QR fit of the co-exposure neutron and photon doses is as follows:

- Neutron dose obtained by the ratio method assumes that the relationship between the neutron dose and photon dose is a constant (e.g., 0.420 for K-25), regardless of the magnitude of the photon dose. For example, using a K-25 EE's measured photon doses of 50 mrem and 100 mrem and the table 5-2 K-25 N:P ratio of 0.420, SC&A calculates neutron doses as follows:

  Calculated neutron dose = 50 mrem × 0.420 = 21 mrem
  Calculated neutron dose = 100 mrem × 0.420 = 42 mrem

The calculated neutron doses are in the same exact ratio as the photon doses, regardless of the magnitude of the EE's measured photon dose. In this example, the neutron dose ratio is (21 mrem/42 mrem) = 0.50, and the photon ratio is (50 mrem/100 mrem) = 0.50 also.

- Neutron dose calculated using an equation derived from a QR fit, such as those listed in table 5-2 of RPRT-0060, does not restrict the assigned neutron dose to a linear function of the EE's measured photon dose but instead allows for the assigned neutron dose to be a nonlinear function of the EE's measured photon dose. For example, using a K-25 EE's measured photon doses of 50 mrem and 100 mrem and the table 5-2 QR relationship for the 50th percentile neutron dose, SC&A calculates neutron doses as follows:

  Calculated neutron dose = (50 mrem × 0.139) + 10 mrem = 17 mrem
  Calculated neutron dose = (100 mrem × 0.139) + 10 mrem = 24 mrem

  The calculated neutron doses are not the same ratio as the photon doses. In this example, the neutron dose ratio is (17 mrem/24 mrem) = 0.71, whereas the photon ratio is (50 mrem/100 mrem) = 0.50.

RPRT-0060 Attachment A, "Quantile Regression Analysis Implementation within IREP": This attachment contains details of the implementation of the QR-derived data in the Interactive RadioEpidemiological Program (IREP) for dose reconstruction (DR). Included are the equations to be used to calculate the lognormal parameters for the N:P ratio for a given photon dose, i.e., geometric mean and geometric standard deviation at the 50th and 95th percentiles. An example is provided for calculating the 50th percentile N:P ratio at 0.050 rem photon dose (normal distribution) using the K-25, PORTS, and Y-12 combined data from table 5-2. The result of the example is an N:P geometric mean of 0.22732, as shown at the bottom of page 23, and a geometric standard deviation of 2.291481, as shown at the top of page 24 of RPRT-0060. A dose reconstructor would then use the Monte Carlo simulation method to derive neutron doses (using a lognormal fit), as illustrated in figure A-1 of RPRT-0060, for assignment in the IREP input table.

3 SC&A's evaluation of RPRT-0060

Shortly after RPRT-0060 was issued, NIOSH published a white paper, "Neutron Dose Assignment for K-25 and Portsmouth Gaseous Diffusion Plants," dated May 6, 2019, which also contained data from Y-12 and PGDP, although the names of these two sites did not appear in the title (NIOSH, 2019; "May 2019 White Paper"). SC&A (2019) evaluated NIOSH's May 2019 White Paper for the Work Group on Gaseous Diffusion Plants. RPRT-0060, issued March 28, 2019, contains essentially the same information that is in the later May 2019 White Paper. Therefore, section 3.1 of this report summarizes SC&A's evaluation, NIOSH's responses, and SC&A's replies concerning the May 2019 White Paper.

3.1 Evaluation of the May 2019 White Paper

September 16, 2019: SC&A issued their review of NIOSH's May 2019 White Paper. SC&A had no findings and three observations (SC&A, 2019).

February 6, 2020: NIOSH responded to SC&A's three observations from SC&A's review of NIOSH's May 2019 White Paper (NIOSH, 2020).

July 13, 2020: SC&A issued a review of NIOSH's February 6, 2020, response to the three observations and added a fourth observation (SC&A, 2020a).

January 20, 2021: NIOSH issued a response in the form of a memorandum to the Work Group on Gaseous Diffusion Plants concerning SC&A's observations (NIOSH, 2021).

The following is a summary of the observations and their resolutions from SC&A's (2019) and (2020a) reviews of NIOSH's May 2019 White Paper (NIOSH, 2019).

- **Observation 1: Apparent inconsistence in use of the lower limit of detection (LOD) (SC&A, 2019):**
    - In 2020, NIOSH responded that the text from the May 2019 White Paper will be revised when this verbiage is added to the site profile technical basis documents (TBDs) to make these approaches clear (NIOSH, 2020).
    - SC&A (2020a) concurs with NIOSH's plan to use consistent LOD terminology in the revised site profiles and SC&A will review the revised TBDs when available.
- **Observation 2: Use of Portsmouth dosimetry values near zero (SC&A, 2019):**
    - NIOSH (2020) responded that uncensored neutron dose data and uncensored photon dose data were available for PORTS, so they were modeled as is. Modeling of complete data, when available, is always preferable to modeling censored data.
    - SC&A found that there is an overarching issue concerning the use of recorded values less than the detection limit. SC&A suggested deferring the use of recorded values less than the detection limit for the GDP neutron dose analysis to that overarching issue (SC&A, 2020a).
    - SC&A concludes that NIOSH's model is a mathematically accurate method for assessing censored bioassay data in the absence of other information (SC&A, 2020b). SC&A considers this observation resolved and recommends closure.
- **Observation 3: Use of the standard N:P ratios versus the quantile-regression and Monte Carlo approach (SC&A, 2019):**
    - NIOSH's response was that quantile regression analysis (QRA) is an established methodology available for use in the project (refer to ORAUT-RPRT-0087, rev. 00; ORAUT, 2018). QRA is the preferred methodology for assigning neutron dose based on photon measurements (NIOSH, 2020).
    - SC&A found that this is also an overarching issue concerning the use of recorded values less than the detection limit in conjunction with the QRA method. SC&A suggested deferring the use of recorded values less than the detection limit and the QRA method for the GDP neutron dose analysis to an overarching issue (SC&A, 2020a).

- As indicated in observation 2, SC&A concurs with the use of data less than LOD values. SC&A is currently reviewing the use of the QRA method.

- **Observation 4 (SC&A, 2020a): Use of neutron plus photon for photon does to calculate N:P**

  - NIOSH (2020) discussed the calculation of PORTS N:P ratios on page 2 of their response paper.
  - SC&A reviewed NIOSH's discussion and found that in deriving the N:P ratio of 0.369 on page 6, and in table 6, column 3, of the May 2019 White Paper, NIOSH (2019) used N:P = n/(n + p) instead of N:P = n/p (where n/p is the neutron-to-photon ratio). This would create a lower-than-normal value for N:P from the PORTS data. If the QRA method is used for DR, as presented on pages 10–24 of the response paper, then the incorrect N:P value of 0.369 would not be used in DRs. However, either the correct N:P values should be derived and used in any revisions to the May 2019 White Paper or future documents, or NIOSH should clarify why the current value is correct (SC&A, 2020a).
  - NIOSH concurs with SC&A's observation. Any corrections or clarifications needed will be made when the site profile TBDs are revised. NIOSH intends to use the QRA method for determining neutron doses, and this will be reflected in the TBDs for both PORTS and K-25 when revised (NIOSH, 2021).
  - SC&A will review NIOSH's revision of the site's TBDs concerning N:P values when available. As indicated in SC&A's response to observation 3, SC&A is currently reviewing the use of the QRA method.

3.2 SC&A's evaluation of section 2.0 of RPRT-0060

As indicated in section 2, RPRT-0060 provides background material in the form of a summary of the various radiological properties of the uranium materials processed at the GDPs and Y-12. The background information in section 2.0 of RPRT-0060 is the only material difference between RPRT-0060 and the May 2019 White Paper. Therefore, SC&A reviewed section 2.0 of RPRT-0060 for technical accuracy and to check the validity of the data in the tables using the appropriate references as provided in the text and footnotes to the tables. SC&A identified one finding and two observations concerning tables 2-1 and 2-2.

3.2.1 Table 2-1

Table 2-1 lists the composition of various uranium materials and two very highly enriched uranium materials from the Savannah River Site and the Idaho Chemical Processing Plant. SC&A verified that the data were correct for the percent by weight (wt %) for uranium (U)-234, U-235, and U-238 listed in the first three rows (NU, LEU, and HEU) using the reference document "Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities" (NAS, 2005, table A-2).

SC&A could not find that the referenced document (NAS, 2005, table A-2) contained the wt % for U-233 or U-236 listed in table 2-1.

SC&A verified the remaining data in table 2-1 using the data from table 5-7 of ORAUT-TKBS-0014-5, revision 03, "Y-12 National Security Complex – Occupational Internal Dose" (ORAUT, 2012) and found the data listed in table 2-1 to be correct, except as outlined in the following finding.

Finding 1: Incorrect values in table 2-1 for recycled NU, LEU, and DU

SC&A found the following errors in table 2-1:

- The recycled LEU mass fraction for U-233 is 0.00E+00 (0 percent) in table 5-7 of ORAUT-TKBS-0014-5 (ORAUT, 2012), whereas RPRT-0060 table 2-1 listed the wt % as <0.01 percent.
- The recycled LEU mass fraction for U-236 is 0.00E+00 (0 percent) in table 5-7 of ORAUT-TKBS-0014-5 (ORAUT, 2012), whereas RPRT-0060 table 2-1 listed the wt % as <0.01 percent.
- The recycled DU mass fraction for U-233 is 0.00E+00 (0 percent) in table 5-7 of ORAUT-TKBS-0014-5 (ORAUT, 2012), whereas RPRT-0060 table 2-1 listed the wt % as 0.001.
- The recycled DU mass fraction for U-234 is 1.000E-5 (0.001 percent) in table 5-7 of ORAUT-TKBS-0014-5 (ORAUT, 2012), whereas RPRT-0060 table 2-1 listed the wt % as 0.2.
- The recycled DU mass fraction for U-235 is 2.000E-03 (0.2 percent) in table 5-7 of ORAUT-TKBS-0014-5 (ORAUT, 2012), whereas RPRT-0060 table 2-1 listed the wt % as <0.0001.

If the incorrect values for wt % (although the difference is small for some of them) from table 2-1 are used to derive the yield values listed in table 2-2, then the derived yield values do not match those in table 2-2. Therefore, SC&A used the mass fraction values from table 5-7 of ORAUT-TKBS-0014-5 (ORAUT, 2012) to derive yield values and compare them to the values in table 2-2.

3.2.2 Table 2-2

Table 2-2 of RPRT-0060 lists the neutron production in various uranium isotopes and materials. Using tables 6-4 and 6-5 of DOE (2009), SC&A verified that the data for U-232, U-233, U-234, U-235, U-236, and U-238, are correct as listed in the first six rows of table 2-2 of RPRT-0060. SC&A then evaluated the remaining data in table 2-2, some of which used the data presented in the first six rows for U-232, U-233, U-234, U-235, U-236, and U-238, with the following results.

Observation 5: Clarification needed for NU, LEU, and HEU fission yield data in table 2-2

For rows 7, 8, and 9 (NU, LEU, and HEU) in table 2-2, SC&A found that the values in table 2-2 (which were derived from the wt % data in table 2-1 (which are correct for NU, LEU, and HEU) and the data for U-232, U-233, U-234, U-235, U-236, and U-238 (as listed in the first six rows of table 2-2) were correct, except for the values for spontaneous fission yield (neutron per second per gram (n/s-g)). These values do not match the values listed in table A-2 of NAS (2005), as shown in table 1. SC&A's derived yield values are similar to those in table A-2 of NAS (2005).

Table 1. Comparison of spontaneous fission neutron yields

Material	RPRT-0060 table 2-2 neutron yield (n/s-g)	NAS (2005) table A-2 neutron yield (n/s-g)
NU	5.45E-3	1.3E-2
LEU	5.31E-3	1.2E-2
HEU	7.69E-2	1.4E-3

For rows 10, 11, and 12 of table 2-2 (high burn-up, lower burn-up, and weapons-grade and very highly enriched uranium), SC&A found that the yield values in RPRT-0060 table 2-2 (which were derived from the mass fraction data in table 5-7 of ORAUT-TKBS-0014-5 (ORAUT, 2012) and the data for U-232, U-233, U-234, U-235, U-236, and U-238, as listed in the first six rows of RPRT-0060 table 2-2) closely matched those derived by SC&A.

For rows 13, 14, and 15 of table 2-2 (recycled NU, LEU, and DU), SC&A found that the values in table 2-2 (which were derived from the mass fraction data in table 5-7 of ORAUT-TKBS-0014-5 (ORAUT, 2012)—not table 2-1 of RPRT-0060, because some of the recycled LEU and recycled DU rows are incorrect—and the data for U-232, U-233, U-234, U-235, U-236, and U-238, as listed in the first six rows of table 2-2) were correct. However, SC&A did have the following observation.

Observation 6: Incorrect information in table 2-2, footnotes b and c

SC&A found that footnotes b and c of RPRT-0060 table 2-2 should refer to table 2-2 (which contains yield data in the first six rows), not table 2-1. Table 2-1 contains wt % data and the other two references listed (table A-2 of NAS (2005) and table 5-7 of ORAUT (2012)) also contain percentage by weight or mass fraction data, respectively. As written, there are redundant references for the radioisotope weight percentages and no reference for the yield values for U-232, U-233, U-234, U-235, U-236, and U-238, such as are listed in the first six rows of table 2-2.

The one new finding and the two new observations discussed in this section are concerned with background information provided in section 2.0 of RPRT-0060 that was not present in the May 2019 White Paper. The finding and two observations would not affect the DR neutron dose assignment recommended in attachment A but the issues they describe should be corrected or clarified.

4 Summary and conclusions

SC&A reviewed RPRT-0060 (ORAUT, 2019) and found that RPRT-0060 contains essentially the same information as NIOSH's May 2019 White Paper (NIOSH, 2019). Hence, SC&A's (2020a) review of the May 2019 White Paper, which is outlined in section 3.1 of this report, applies to RPRT-0060 (ORAUT, 2019). Additionally, SC&A's observations (and their resolution or current status) about the May 2019 White Paper are equally applicable to RPRT-0060. SC&A also reviewed section 2.0 of RPRT-0060 concerning information that was not contained in the May 2019 White Paper and gave the results of that review in section 3.2 of this review.

In total, there was one finding and six observations. The status of these are as follows:

- **Finding 1 (new this review): Incorrect values in table 2-1 for recycled NU, LEU, and DU.** This is a new finding concerning section 2.0 of RPRT-0060 for NIOSH to respond to.

- **Observation 1 (SC&A, 2019): Apparent inconsistence in use of the lower limit of detection (LOD).** SC&A concurs with NIOSH's plan to use consistent LOD terminology in the revised site profiles.

- **Observation 2 (SC&A, 2019): Use of Portsmouth dosimetry values near zero.** Resolved. SC&A recommends closure.

- **Observation 3 (SC&A, 2019): Use of the standard N:P ratios versus the quantile-regression and Monte Carlo approach.** SC&A is currently reviewing the use of the QRA method.

- **Observation 4 (SC&A, 2020a): Use of neutron plus photon for photon does to calculate N:P.** SC&A will review the N:P values in the revised TBDs when available. SC&A is currently reviewing the use of the QRA method.

- **Observation 5 (new this review): Clarification needed for NU, LEU, and HEU fission yield data in table 2-2.** This is a new observation concerning section 2.0 of RPRT-0060 for NIOSH's consideration.

- **Observation 6 (new this review): Incorrect information in table 2-2, footnotes b and c.** This is a new observation concerning section 2.0 of RPRT-0060 for NIOSH's consideration.

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